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A FINAL REPORT TO THE

ENVIRONMENTAL PROTECTION AGENCY

VOLUME I

REPORT NO. F-1295 NOVEMBER 1971

FOSTER WHEELER CORPORATION

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16. Abstracts

The fuel properties of refuse and the mechanics and combustion technology associated with the utilization of refuse as a fuel in generating utility grade steam were systematically assessed. By estimating the inventories and compositions of refuse that would likely occur, the extent of SO_2-abatement that might be realized in using refuse as a partial coal substitute was projected through the year 2000. Ten different combined-fuel (coal + refuse) fired boiler configurations were conceived and then analyzed in terms of process variables (plant power capacity, fuel-ratio, etc.); performance/cost characteristics were also predicted. Similarly treated were five plans for modifying existing plants to refuse-burning systems. At least one of the systems within the first group was identified as being a more cost-effective approach to refuse disposal than is landfill. The cost model was developed to consider all the major elements involved in the erection and operation of the candidate refuse-burning systems. Two new-plant configurations were extracted and subjected to detailed engineering analysis. Cost estimates were iteratively computed for the resulting preliminary designs.

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Special mention of noteworthy contributions of other individuals will be found on various pages of this report. It would be improper, however, not to cite at once the outstanding work done by the Project Engineers of the subcontractor firms. At Foster Wheeler Corp., this worker was Mr. R. E. Sommerlad, who furnished some of the most important data developed on this study. At Cottrell Environmental Systems, Inc., the key inputs there resulted from the efforts of Mr. A. P. Konopka.

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ABSTRACT

Because of the SO_2 problem, coal is being displaced as a power plant fuel in certain areas by other, more costly fossil fuels of lower sulfur contents. Urban refuse can also be considered a coal substitute because, even with mass/energy relationships considered, sulfur inputs from refuse should be much lower than from equivalent amounts of coal. The questions are of course can practical, refuse-fired steam generators be built for base load utility service, and can this process be made competitive with other, presently preferred practices of waste disposal? The work described here was addressed to the acquisition of answers to these questions, which, in each case was positive. This involved a systematic assessment of the fuel properties of refuse and of the mechanics and combustion technology associated with the utilization of refuse as a fuel in generating utility grade steam. By estimating the inventories and compositions of refuse that would likely occur, the extent of SO_2-abatement that might be realized in using refuse as a partial coal substitute was projected through the year 2000.

Determining the useful energy from refuse involved the associated task of establishing for this fuel its behavior in and compatability with furnace structures. This required the definition of the various energy utilization opportunities for which refuse might be suited. With emphasis selectively aligned to power plant applications, the relevant technology and state-of-the-art (particularly in Europe) of power generation with refuse, other waste fuels, and non-bituminous solid fossil fuels were documented. In this connection, pertinent processes and hardware used in the handling and conditioning of refuse were also reviewed. Criteria were then established for firing refuse in utility-class boilers.

A catalog of ten different combined-fuel (coal + refuse) fired boiler configurations was conceived and then analyzed in terms of process variables (plant power capacity, fuel-ratio, etc.), performance/cost characteristics were also predicted. Similarly treated were five plans for modifying existing plants to refuse-burning systems. At least one of the systems within the first group was identified as being a more cost-effective approach to refuse disposal than is landfill at the present time. This advantage may well also be implicit in other of the candidate systems but, due to the limitations of the analysis, this could not be resolved. One limitation was that cost data on refuse processing and performance information on furnaces firing shredded refuse in suspension were lacking, this necessitated the adoption of conservative costs and design specifications for certain components examined in the analysis.

Another limitation was that the comparative refuse transportation costs for landfill disposal and energy-recovery installations could not be developed. It is highly likely that, in many of the metropolitan areas of the U.S., the combined costs of transportation and disposal will be lower than for existing and/or projected landfill operations. A third limitation was that the conclusions derived could not be expected to maintain their validity in the dynamic economic situation that has prevailed. The July 1969 cost bases used are probably already quite obsolescent, but because fuel costs are escalating at a much greater rate than capital costs, the cost effectiveness of the analyzed technique has probably significantly increased.

These limitations not withstanding, the cost model was developed to consider all the major elements involved in the erection and operation of the candidate refuse-burning systems. From this systematic analysis, two new-plant configurations were extracted and subjected to detailed engineering analysis. Cost estimates were iteratively computed for the resulting preliminary designs. Where technical knowledge-gaps were recognized, research and development requirements were itemized. These were analyzed and integrated into discrete task packages. Final organization of these R&D elements took the form of two suggested five year plans, each structured to accommodate a specific level of effort.

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I. SUMMARY AND CONCLUSIONS

A. INTRODUCTION

At the present time, urban refuse is being collected in the U.S. at a rate of almost 200 million tons per year. Predictions, variously derived, suggest that this output will be doubled or even tripled by the end of the century.

The current preferred method of disposal is sanitary landfill, although less acceptable forms of refuse dumping are still being widely practiced. Yet even today some American cities are already on the verge of exhausting fill-tracts that are within reasonable logistic reach of their waste collection networks. As landfill costs increase, due to site remoteness or high costs of nearby real estate, and surpass incineration costs, shift-over to the latter is indicated. But converting over to incinerative disposal is often regarded with reluctance because it (1) is an expensive proposition on the short term, (2) involves a variety of interfaces with local air quality standards, and (3) affords only volume reduction, the residues from which must still go to landfill. The net managerial action may thus tend to be one of continuing to absorb higher and higher disposal costs until incineration becomes unavoidable. Fortunately, this type of quandary is not yet a widespread one.

High costs and concern over the introduction of new sources of air pollutants need not relegate refuse-incineration to the position it now suffers. Refuse can be successfully incinerated in the furnace of a power boiler. Such a process not only produces power credits and thus reduced disposal costs, but can lower SO_2 levels. This is because refuse has a much lower sulfur content than does most American coal. The concept is hardly new. It has been extensively applied throughout Europe and elsewhere over the past decade. It is now being introduced to North America at a number of points. The results obtained will doubtless be followed with great interest over the next several years.

Because of the importance that the refuse- or combination- (refuse + fossil fuel) fired boiler holds for air pollution control and waste management agencies, guidelines should be established to insure optimum pay-offs. This is, in essence, the purpose of the present report.

Of the number of findings developed in this study, the following can be highlighted:

- Quantities of urban refuse collected will probably have increased 180% during the period 1965-2000, or to about 450×10^6 tpy.

- The higher heating value (HHV) of urban refuse will probably have increased 30% by the year 2000, or from a present value of about 5000 to 6500 BTU/lb.

- If all U.S. urban refuse were fired, it could displace considerable power plant coal - 25% now, increasing to 38.4% by the year 2000. Coal firing is only regionally practiced and not necessarily near refuse production centers, so that achievable displacements would be much lower.

- Using all available refuse in a selected LMA (Large Metropolitan Area) to displace some coal in uncontrolled power plants would reduce the SO_2 and particulate burdens (from all sources) by about 7% and 21%, respectively. If the power plants used SO_2 and particulate control equipment, the reduction of the (then lowered) total burden would be inconsequential.

- Combination-fuel fired systems have been identified that would furnish disposal costs which are lower than by sanitary landfill.

- Steam generators equipped with agitating grates generally proved to be more cost effective than those employing some form of suspension firing.

- Corrosion is not a serious problem. It can be essentially eliminated by firing refuse and coal in separate furnaces wherein the refuse does not heat the working fluid much above 750° F and the coal is used to produce final steam conditions.

- If correct refuse/coal heat input balances are observed and proper boiler designs utilized, base load systems compatible with modern turbogenerators are entirely practical.

The present program was undertaken under Contract No. CPA 22-69-22 for the National Air Pollution Control Administration. The prime contractor for this work was the Envirogenics Company, a Division of Aerojet-General Corporation. Extensive subcontractor inputs were furnished by the Foster Wheeler Corporation in the field of steam generator technology and design. The subcontractor providing services in the field of air pollution control methodology was Cottrell Environmental Systems, Inc., Division of Research-Cottrell, Inc.

B. PROGRAM OBJECTIVES AND APPROACH

1. Project Scope

The purpose of the present program was to determine the characteristics of systems, that would be optimal in terms of the state-of-the-art technology, for using refuse as a low sulfur fuel for power generation, and to determine the overall potential of using such systems to decrease the total emissions from the incineration of refuse, and to assist in reducing sulfur pollution now resulting from fossil fuel combustion. These broad objectives were approached as outlined in the following paragraphs, which describe the scope of the program.

a. Assessment of Refuse as a Fuel

Based on published and solicited data, the quantities of refuse generated in the U.S. would be estimated for the period extending from the present to the year 2000. These estimates would apply not only to the national situation but to those expected for six LMA's selected because of high sulfur oxide burdens and waste disposal problems. For the same regions and time period, projections were also to be developed for the compositional (gross, chemical, and calorific) changes in refuse that might be expected, taking into account those factors, such as packaging industry trends, that influence refuse composition. From these bases, the maximum potential abatement in sulfur oxides, particulates and other pollutants emitted from power plants would then be derived assuming that all refuse in the areas of interest would be used to displace an equivalent amount of fossil fuel energy.

Chemical and physical property data would be collected and interpreted to determine the reactions of combustion products of all combinations of refuse and fossil fuel and the compatability of these products with the gas-side surfaces of conventional boilers. Consideration would be given to: (1) the expected completeness and rate of reaction of refuse ash and fly ash with sulfur compounds, including SO_2, in the combustion products from coal and fuel oil; (2) the expected reaction of coal and fuel oil ash and fly ash with halogens and any other corrosive or deposit-forming constituents in the products of refuse combustion; and (3) the determination of the desirable proportions of refuse/fossil fuels that would minimize SO_2 release and boiler tube wastage and maximize the performance of electrostatic precipitators and other collectors.

Possible requirements for conditioning refuse fuel, such as size reduction, drying, addition of materials (e.g., dolomite or limestone) would be established. In this context, emphasis would be placed on the preparation of refuse for suspension firing.

Through solicited and published data, the performance and cost characteristics of refuse grinding equipment would be established. Similarly, the characteristics of ground refuse would be determined in terms of size ranges and component types by sample taking and sorting operations. Using Stokes Law calculations and appropriate empirical shape factors, typical furnace gas velocities and circulation patterns, the residence times of suspension-fired particles of various sizes and types would be estimated. These data would then be correlated with the estimated burning times and percent burnout of ash for maximum particle sizes.

Taking into consideration important social and political factors that might be controlling, the engineering and economic aspects of bulk handling, sorting, and transporting refuse before, during, and after processing would be examined. This would be done to determine the economic constraints and optimum modes of moving refuse to firing sites. Areas where essential knowledge or data are lacking would be identified, including less common but relevant operations, such as pipe transport of slurried or dry refuse.

b. Assessment of Power Plant Designs

In order to establish a foundation for design developments, a state-of-the-art survey was to be made of wet- and dry-bottom steam generators fired with both conventional and unconventional fuels, with particular emphasis being placed on selected examples of European power plants (a minimum of two) firing mixed fuels. In addition to the basic design parameters, data were to be developed on fuel composition, heat and material (including sulfur) balances, boiler efficiencies, residue and fly ash properties, APC equipment performance, and the nature of any erosion, corrosion, or fouling problems experienced.

From this information base, preliminary engineering designs of optimum, refuse-firing utility boilers would then be generated. This catalog of system possibilities would include necessary flow sheets and tabulations of key process and cost data. Candidates for each of the following types of applications would be provided by this design effort:

- A new refuse-fired installation in which fossil fuel would be employed only as an auxiliary fuel.
- A new installation in which refuse/fossil fuel blends would be routinely fired.
- An existing central station boiler, modified to accommodate the use of refuse as a fuel.

Using standard accounting practices of the electric utility industry, net costs per kw-hr generated by the various systems would be estimated. The net charges for disposal per ton of refuse that would have to be made to the municipality by the utility operating the system would then be determined as a function of return on capital. The cost of power generation and refuse disposal for the several systems would then be compared with the costs of power generation by conventional means and by incineration without heat recovery. Any net savings in fuel costs, capital investment, or other expenses would be identified. In these cost analyses, the probability that SO_2 control and more efficient particulate control equipment will be required would have to be considered. In each type of system, the economic and political factor associated with the optimum integration of the proposed designs into the overall power generation and waste disposal complex would be considered.

c. Development of Recommendations and Formulations of R&D Plans

Implementation of the outputs of the study could well require a systematic R&D approach in order to arrive at full-scale proving of steam generator designs considered optimal. Workable R&D plans would therefore be developed that would solve any techno-economic problems identified on the program and provide for the fundamental through scaled-up operations necessary to evaluate whole systems or components thereof. The constituent R&D tasks, along with the estimated time and costs required for their performance, would be described and incorporated into one or both of two separate 5-year plans. Each of these plans would be scaled at a discrete level of effort — 5 and 25 million dollars, respectively. The relationships of the various task elements therein would be systematically defined and a logical sequence of R&D operations would be recommended.

2. Information and Data Sources

The information matrix developed for the sustenance of the present program involved inputs from many different sources. A considerable breadth of the open literature was of course reviewed. Key items were abstracted, and committed to a storage system for timely retrieval. Appendix D is a bibliography of the key material which entered the study. Of the foreign-language publications, those in German proved to be the most pertinent as well as the most prolific. A bulk of the necessary translations was rendered by Mr. E. J. Lachner of Foster Wheeler Corporation.

Field surveys were conducted in both this country and in Europe. A large portion of the data presented in Appendix B was obtained as a result of such activities.

A number of leading authorities prominent in the several fields pertinent to this study were consulted. To avoid any implication of hierarchy, the following list of these specialists has been prepared in alphabetical order.

Consultant	Affiliation
Dr. -Ing. M. Andritzky	Stadtbaudirektor a. D. (Munich)
Mr. L. P. Flood	Private Consultant
Mr. A. E. Gosselin, Jr.	Private Consultant
Prof. J. B. Howard	Massachusetts Inst. Tech.
Prof. E. R. Kaiser	New York University
Mr. A. Michaels	Private Consultant
Dipl. -Ing. F. Nowak	Technische Werke der Stuttgart
Prof. B. H. Sage	California Inst. Tech.
Prof. A. F. Sarofim	Massachusetts Inst. Tech.
Prof. D. G. Wilson	Massachusetts Inst. Tech.

A source of data of considerable importance on the present program was the documents furnished by the Technische Überwachungs-Verein (TÜV). This organization, in addition to other activities, comprises a neutral apparatus for conducting acceptance tests on power boilers in Germany. Detailed test reports for five modern refuse-burning steam generators were obtained from the TÜV, translated, and evaluated. A great deal of this data, in condensed form, is contained in Appendix B (Section V).

Correspondence also served as a vital link in the information gathering process. Much of the data on the LMA's was obtained in this manner, as were important inputs from Government officials, equipment manufacturers, researchers involved in related work, and managers of operating and under-construction waste-fuel fired boilers.

Some laboratory work was also performed during the present study. The analysis and characterization of deposits removed from refuse-fired steam generators in Germany are reported in Appendix A (Section II). Time was also devoted to the determination of size-reduction patterns effected by refuse grinding machines. This work is reported in the present volume (Section II, D) and involved a praiseworthy degree of cooperativeness on the part of Heil Co. and the City of Madison, Wisconsin, the Stanford Research Institute, and the Eidal International Corporation.

Engineering drawings of existing boiler systems were largely furnished by the Foster Wheeler Corporation in fulfillment of their partnership on the present work. Additional drawings and other important information were, however, also provided by Combustion Engineering, Inc., and the Babcock and Wilcox Co.

3. Report Organization

As a review of the Table of Contents will reveal, the initial discussions in the report have gone to the characteristics and availability of refuse relative to the intended application. Following this, data are presented on the combustion products of refuse and the implications these products may have in terms of damage to the environment or internal furnace structures. Appendix A, which has been isolated from this discussion, specifically deals with wastage and fouling associated with refuse firing. This particular documentation represents an extensive condensation of a series of informal treatises produced by Mr. R. W. Bryers of Foster Wheeler Corporation. The original unedited material has been delivered to the EPA.

The elucidation of refuse combustion-product parameters lead on to the consideration of the extent pollutant levels might be reduced. This topic is approached (in Section II, C) on the sensible basis of viewing coal as the high sulfur fuel that would have to be displaced. The effect that refuse and APC equipment would play in this fuel improvement is factored into a 30-year forecast for 6 LMA's*.

Before commitment to the main topic of power boiler technology, yet two more introductory topics are dealt with. Section II, D provides a survey of current information on refuse handling, conditioning, and transport processes. The intent is to update, in that a very comprehensive treatment of this subject was produced not too long ago. Included are viewpoints on the thermodynamic behavior of fired-refuse as a function of shape and size and the aerodynamic properties of the fluid phase. This topic is of considerable interest to design concepts later discussed. Section II, E serves as a prologue to the application intent of this report, and suggests alternative opportunities that might be considered for harnessing the impressive potential energy available from urban waste.

The next main Section of the report (III) is dedicated to the development and evaluation of suitable furnace configurations for firing refuse. It is initiated, properly, with a fairly extensive survey of the state-of-the-art of boiler technology and European practice in using refuse to generate electricity. This is contained entirely in Appendix B. As mentioned earlier, an important ingredient of this survey was the information previously furnished by the TÜV. While only a small fraction of the TÜV data could be practically reported in this document, translations were made of all pertinent sections of the reports.

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*New York, Chicago, New Haven, Philadelphia, St. Louis, and Washington, D. C.

Section III, B of the report develops in considerable depth the criteria which must be observed in considering refuse as a power plant fuel. From these bases are then presented ten candidate configurations of new central station units suitable for generating grid-electricity while disposing of urban refuse. An additional five systems are also considered which would involve the modification (retrofit) of existing utility-class boilers for the same purpose. Ideas are then developed that go to APC equipment requirements and, more importantly, the waste handling apparatus necessary to make such power plants function successfully.

In Section III, C, the engineering concepts presented previously are subjected to a systematic cost analysis. New and retrofit refuse burning power plants are treated separately. Cost models for new plant designs, detailed in appendix C, are developed and costs are determined for ten selected refuse/coal firing power plant configurations and for analogous coal firing plants. Cost model trade-off study results are presented and two candidate refuse firing power plant configurations are subjected to detailed cost optimization studies. The five power plant configurations selected as retrofit candidates are individually cost analyzed. Retrofit and operating costs are defined and refuse disposal cost comparisons are made.

Section IV deals with the matter of how the findings of the report are to be implemented and reduced to profitable practice through, (1) immediate technological opportunities, and (2) progressive R&D operations.

The final portions of the report are contained in Appendices D and E, which consist, respectively, of the bibliography, previously mentioned, and a glossary of terms.

C. CONCLUSIONS AND RECOMMENDATIONS

1. Refuse as a Fuel

a. Quantity-Quality Considerations

It is estimated that the national population will have increased by almost 60% by the end of the century. Because of the changing living styles and other factors, the per capita production of mixed municipal refuse will also increase. On the most probable basis, the national "resource" of refuse will have increased by a factor of 2.8, or from about 160 to 450 million tons per year, between the years 1965 and 2000. A factor as high as 4.0 is also possible.

With the introduction of more garbage disposal units, the substitution of more plastic for glass and metal goods, and the acceptance of more new items of short-lived (one-time-use) merchandise, the composition of urban refuse can also be expected to undergo change. The following tabulated predictions are considered to be reasonable.

PROJECTED COMPOSITIONAL CHANGES IN U.S. URBAN REFUSE

	Composition, Wt-%						
Year	Garbage	Plastics	Glass	Metals	Garden	Paper	Residual
1970	20	2	12	10	12	38	6
2000	6	13	7	5	12	55	6

The composition of municipal refuse at a given location varies fairly widely in both the short and long (seasonal) scale. Physical analyses of solid waste over a period of a week or so in the same area show wide variations and seasonal effects on such constituents as garden wastes account for most of the variation through the year. The most striking thing about the geographical variation in refuse composition is that it is so small. Aside from the geographical effects on amounts and peak-appearance of garden wastes, municipal refuse is much the same the country over. This may merely be caused by the homogeneity of the culture in the U.S. From the point of view of refuse as a fuel, its physical analysis is unimportant except insofar as it determines the heat of combustion and, to a degree, corrosion potential. Because the seasonal variations in waste load result largely from low-Btu, high-moisture yard and garden wastes, the approximately ± 8% variation in average waste load introduces only about a ± 6% variation in total heat available from refuse over a year in a typical case. The heat of combustion of refuse has grown steadily over the past several decades, but will probably not grow as fast during the next three. Based on the compositional changes shown above, an approximate 30% growth, from about 5000 Btu/lb in 1970 to about 6500 Btu/lb in 2000 AD, can be expected.

b. Reduction in Pollutant Emissions

At the present time, if all the urban refuse generated in the U.S. were to displace an equivalent amount of coal energy, approximately 25% of the coal now fired in power plants could be saved. By the year 2000 this displacement will probably have increased to almost 40%. This projected increase will be due not only to the enhancement in fuel value that refuse is undergoing, but to the probability that, on a per capita basis, refuse generation will increase at a faster rate than the demand for electricity that can be satisfied by fossil fuel energy. This prediction may prove to be in serious error if the problems now encountered in the construction of nuclear power plants persist.

It is well known that the sulfur content of refuse is low in comparison with that of coals and residual oils. Thorough review of the literature shows a consistent average sulfur content of 0.1 to 0.2% in U.S. refuse. This contrasts with a range of 2.5 to 3.5% for those bituminous coals most commonly being fired in power plants. Correcting for the differences in heats of combustion, sulfur input to the boiler could be reduced by a factor of from 5 to 15. It is also well documented, however, that substantially all (95 to 100%) the sulfur in coal or oil fired to a boiler will appear in the flue gas as the oxides. Data available for refuse incinerators indicate that only somewhere between 25-50% of the input sulfur is released as SO_2. This is doubtless due to the fact that a significant portion of the sulfur present in trash is in the inorganic salt or fixed form. Thus if all the urban refuse now available in the U.S. were to displace 2% S coal, over 2-1/2 million tons of SO_2 would be eliminated from the atmosphere annually. This is based on the premise that no SO_2 control would be practiced, which is essentially the case now, and that the percent of input sulfur released as SO_2 is 95 and 50%, respectively, for coal and refuse.

Evaluation of data on particulate release rates for power plants and refuse incinerators indicates that about the same amount (2-1/2 million tons per year) of particulates as SO_2 could be eliminated. This, however, is also based on a no-control situation, which is obviously unrealistic. Only about 120,000 tons per year would be eliminated if all the power plants involved were equipped with APC equipment having an average efficiency of 95%. The reason for the higher particulate release rates for coal is explicit from the modes of firing. Refuse is usually burned, without prior size reduction, on grates, while coal is fired in pulverized form in suspension. If shredded and fired in suspension, refuse would doubtless generate more fly ash, but certainly not to the extent of 80 or more percent of its inert content, which is typical for coal. The ash particles formed would still be much larger from shredded refuse than from pulverized coal, and would contain large amounts of dense materials (e.g., glass and metal) that would be less susceptible to elutriation than coal ash.

Because total consumption of the national refuse inventory in power boilers is unlikely, the more realistic model is the LMA. Using the St. Louis area, as an example, it was found that if all the available refuse there were fired in power boilers to replace part of the coal, there would result a SO_2 reduction of about 31,000 tons per year. Based on the SO_2 burden from all sources, this would represent a reduction of about 7%. The reduction would only amount to 0.5%, however, if the power plants were equipped with SO_2 scrubbers of 95% efficiency. In the case of overall particulate burden, a reduction of 21% would be experienced if no APC equipment were being used on any power boiler. This reduction would be only 1%, however, if particulates from all power plants were being removed by air cleaners with a 95% efficiency.

Coal displacement by combination firing with refuse will in itself obviously not completely solve the SO_2 problem and clearly the development of APC systems for removing this pollutant will still be necessary. An important aspect of the refuse utilization concept is the mode in which it would be fired. The argument could be raised that the firing of refuse with reduced amounts of coal in a single furnace chamber would actually provide little, if any, benefit. Scrubbers would still have to be sized on the basis of flue gas volume and this would increase as the refuse proportion was increased. Annualization of this added cost might then actually exceed any operational cost reduction that would be realized by a diminished rate of sorbent exhaustion. As will be discussed later, however, the preferred configuration of the combined-fired power boiler involves an almost complete isolation of the refuse and fossil-fuel furnace components. Thus, in terms of SO_2 removal, the volumetric cleaning requirement would be reduced in a linear manner with respect to the amount of coal displaced by refuse.

c. Processing Technology

Recent advances and developments in the field of refuse processing were reviewed. While considerable new process technology and innovation was noted, little of it had any practical value for the design objectives of the present study. With further development and application work, a number of interesting concepts could well mature as adaptable system components for refuse-firing power plants.

Included in this survey was of course refuse reduction hardware. Because refuse grinding is a somewhat recent application for such equipment, accurate cost data or information on product size-distribution could not be obtained from many of the manufacturers contacted. Output samples were obtained and characterized for two types of machines at Madison, Wisconsin, and Albuquerque, New Mexico.

Developments in the field of ground-refuse conveyance, classification, and salvage were evaluated and documented. This included some brief but interesting testing of Stanford Research Institute's Zig-Zag Separator.

The last area analyzed dealt with the most critical stage in the processing of refuse; that is, the burning process itself. Because considerable experience has been acquired in firing refuse on agitating grates, this analysis was confined to suspension firing mechanisms. Here relatively little is known except for what has been demonstrated in the firing of other type wastes. A theoretical treatment of the subject suggested that the burn-out time required for the larger refuse particles would far exceed the length of time they could be expected to remain suspended. This would suggest that some kind of retainer grate would be indispensable in the suspension-fired furnace. This conclusion will have to be tested, however, because any thermodynamic considerations must incorporate many unavoidable assumptions and simplifications that tend to promote fallibility.

d. Thermal Utilization

While the obvious application of a combined-fired boiler would be the production of electricity, other energy utilization schemes should not be overlooked. In fact, refuse energy need not even be exclusively considered in the context of the Rankine Cycle. This possibility is now being explored with the CPU-400 System, which consists of a fluidized-bed refuse furnace used as a gas generator to drive a gas turbine and coupled power generator. Because of its in-development status, however, this system, as well as others, were not considered to be candidates ready for the present analysis.

A number of alternate uses for steam generated by refuse (or any fuel, for that matter) have been reviewed. None was regarded as offering a strong challenge to the power plant concept, yet most would probably be acceptable if a favorable application situation existed. For example, district heating would be an attractive means of dispensing refuse energy, although during summer months an alternate form of heat extraction (e. g. , through absorption refrigeration) would be necessary. Evaporative water desalination units would also be excellent devices in which to convert refuse to credits. However, only a limited number of such installations would likely be built within reasonable reach of a municipal refuse-collection system.

2. Power Plant Designs

a. Engineering Criteria for Candidate Systems

A survey of the state-of-the-art of domestic and foreign power plant designs was conducted with the aim of identifying those most amenable to combined firing of refuse and fossil fuel.

Pulverized-coal-fired utility steam generators in service include horizontally - and tangentially - fired furnaces, both wet-and dry-bottom, as well as cyclone furnace units; however, units being sold now are virtually restricted to dry bottom, horizontally - or tangentially fired systems. In this country, natural circulation boilers are now the dominant design form in the size range appropriate for refuse-firing (500 MW or less because of refuse logistics). In Europe, however, the once-through system still appears to be the favorite.

From the point of view of combined firing of municipal refuse in utility-type steam generators, no experience is, as yet, available in North America. This practice has grown in Europe, almost entirely in the last decade, and is most advanced in Germany. European practice involves reliance on various refuse burning grates, with pit and crane refuse handling, but with a variety of steam generating arrangements.

All presently operating, large North American steam-generating, refuse-disposal plants use conventional, agitating grates and generate steam at such moderate pressures and temperatures as to be unsuitable for turbo-electric applications. All except the incinerator at the Naval Base at Norfolk, Virginia, fire refuse only; the Norfolk unit fires a combination of oil and the solid wastes collected at the base. It was, however, the first water-walled refuse incinerator built in North America. Water-walled, steam generating incinerators are now under way in Hamilton, Ontario, Braintree, Massachusetts, Harrisburg, Pennsylvania, and Chicago. A recently completed plant in Montreal is in its initial shakedown operation. Again, all of these systems are low - or moderate - pressure units.

Current domestic technology in bark-, bagasse- and wood chip-fired heat recovery furnaces is pointing the way to advances over the present state of the art of refuse combustion, which is almost universally based on the use of the reciprocating or turning grate. The installation now under construction at East Hamilton, Ontario, will utilize the next logical advance in refuse combustion, namely the spreader-stoker equipped with a burnout grate. Planned for test in the near future in St. Louis is the suspension firing of shredded refuse in a grateless furnace, actually an old, coal-fired utility boiler modified for such service. A similar system is under construction in Rochester, New York, although it will have a burn-out grate, as does its bark-burning prototype at Muskegon, Michigan.

Variations in steam flow of ± 30 to 40% have been observed in grate-fed steam generating incinerators both here and abroad. These fluctuations can have periods of from 15 to 25 min., with maximum Δp-rates of from 2 to 8% per min. These wide fluctuations can be greatly reduced by suspension or spreader-stoker firing of ground refuse. This would result from the combined effects of size reduction, mixing, better contact with combustion air, and the reduction in furnace load of unburned fuel. Another engineering approach, particularly desirable if the agitating grate is to be used, would be to employ separate refuse- and coal-fired furnaces. The latter, which are far more susceptible to control, could thus be used to develop the final steam conditions required for the system, and thus even out fluctuations introduced by the refuse-fired portion of the boiler. A secondary benefit would be that the refuse furnace could then be operated at lower steam temperatures. This would serve to reduce the corrosion effects that sometimes occur on tube surfaces in refuse-fired boilers when steam temperatures are allowed to exceed 800° F.

The conservative viewpoint in the U.S. has been that corrosion resulting from refuse combustion would not permit its use in modern, high-pressure, high-temperature, steam generators. Reports of severe corrosion in the several modern combined-firing steam generators in Europe circulated soon after their start-up, and are still repeated. Discussion by project personnel with the plant operators and others confirms an opposing view, that tube wastage, while expectedly greater than with fossil fuels, is a nuisance rather than a severe problem. Tube-wall corrosion rates were initially high but soon levelled off to tolerable rates, apparently after the tubes became coated with protective deposits.

Based on the considerations discussed above, the boiler designs developed on the present program were limited as to refuse input, generally at 60% of the energy. Steam conditions were also approached on a conservative basis, particularly as the refuse input approached the specified limit. The steam generators and other components sensitive to flue-gas flow rates were sized for 50% excess air for refuse-firing and 18% excess air for the coal. These criteria were established on the basis of German practice. Design exit-flue-gas temperature was set at 450° F, which is considerably higher than current practice in utility power plants. This temperature selection was based on performance constraints imposed by the use of an electrostatic precipitator and the resistivity characteristics of refuse fly ash.

Based on the holding limits of commercially available grates, the maximum unit refuse capacity adopted was 1000 tpd for furnaces equipped with agitating grates and 2000 tpd for those with sloping, fall-out retainer grates or none at all. An upper limit* of refuse input per plant was arbitrarily set at 8000 tpd, although it was recognized that a system of such great size would only be feasible if unique refuse in-haul techniques were utilized. The capacity range for individual units was derived along similar lines and the limits set at 85 and 500 MW, the latter being highly unlikely of attainment unless a very low refuse proportion were employed. Because nameplate rating would not exceed 500 MW, it was then logical to utilize natural circulation steam circuitries. Systems having capacities of less than 85 MW, which would perhaps be appropriate for smaller communities, were not considered because refuse disposal costs were found to be unacceptably high at the low refuse rates entailed.

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*for analytical purposes.

Another aspect of the design approach included provision for both SO_2 control (limestone wet-scrubbing with flue gas reheat) and dust control. The latter would be handled by an electrostatic precipitator for the flue gas from the refuse-fired furnace and by the limestone wet scrubber in the coal furnace flue. If the flue gases were blended prior to the air cleaner, an appropriately sized wet scrubber would alone be used to remove SO_2 and particulates for the entire system. Control of HCl and certain other gaseous emissions identified with refuse incineration did not fall within the scope of the present study. Such control may well develop as a requirement of the future, as the composition of refuse changes.

Refuse handling procedures commonly practiced in U.S. incinerators and even in European steam-generating plants are based on a flow arrangement wherein bridge cranes move the feed from furnace-house storage pits to the furnace charging chutes. Alternative, more cost-effective designs are now being explored. These are for systems for which all input refuse must be shredded. Live-bottom receiving and storage structures have been specified and the movement of the shredded feed material is by means of conveyors or pneumatic pipelines. In the present study, it was found desirable to specify similar handling equipment whether the input were to be shredded or not.

Observing the various criteria discussed above, a total of fifteen designs of utility-grade, refuse-firing, steam generators were developed. Ten of these were new-construction schemes, while five were intended to be used in converting (retrofitting) existing, older-generation boilers to combination-fuel service. The latter are described later in this introductory discussion; the ten new-construction systems are summarized for the size range from 100 to 500 MW in Table I-1. Many of the systems described there, however, were actually parametrically analyzed over the size range from 25 to 500 MW and the refuse-input ranges or points compatible with each of the designs.

The refuse disposal costs shown are based on the economic modeling described in the next section and include all operations, including residue disposal, following refuse receipt at the site. All of the systems involve the firing of coal, the fossil fuel selected because of its typical high sulfur content, in combination with refuse.

a

TABLE I-1

SUMMARY OF SYSTEM CHARACTERIST
REFUSE-FIRING STEAM GENERATOR
OVER THE RANGE 100 TO 500 M

Candidate	System Description	Permissable Furnace Frac. Heat Input from Refuse (100/500 MW), %
Case 1	Refuse (on reciprocating grates) and pulverized coal are fired in separate furnaces and the flue gases combined to heat common convection sections. Fuel ratio is determined by size and design heat release rates of furnaces.	0-60/0-60
Case 2	Refuse (on reciprocating grates) and pulverized coal are fired in a completely common furnace. Fuel ratio is not fixed.	0-60/0-60
Case 3	Refuse is fired on reciprocating grates in a separate furnace to generate feedwater for pulverized coal fired steam generator. Fuel ratio is limited. Flue gas flows are isolated.	10.6-16.6/ 10.6-24.9
Case 4	Refuse is fired on reciprocating grates in a separate furnace to generate saturated steam for a pulverized coal fired superheater. Fuel ratio is fixed. Flue gas flows are isolated.	62.5/58.3
Case 5	Shredded refuse is fired in a spreader stoker furnace to generate partially superheated steam for a separate, pulverized-coal fired superheater. Fuel ratio is fixed. Flue gas flows are isolated.	75.5/71.3
Case 6	Shredded refuse and pulverized coal are blown into and fired in a completely common furnace of the conventional, suspension-fired type. Fuel ratio is not fixed.	-60/0-60

B

TABLE I-1

SUMMARY OF SYSTEM CHARACTERISTICS OF REFUSE-FIRING STEAM GENERATOR DESIGNS OVER THE RANGE 100 TO 500 MW

on	Permissable Furnace Frac. Heat Input from Refuse (100/500 MW), %	Design Waste Rate Corresponding to Frac. Waste Heat Input (100/500 MW), tpd	Steam Conditions^1 Corresponding to Frac. Waste Heat Input (100/500 MW)
pulverized coal are e gases combined Fuel ratio is deter- e rates of furnaces.	0-60/0-60	0-2278/0-9650^3	C-A/D-A
pulverized coal are e. Fuel ratio is not	0-60/0-60	0-2278/0-9650^3	C-A/D-A
es in a separate verized coal fired ed. Flue gas	10.6-16.6/ 10.6-24.9	317-500/1364-3408	C/D
es in a separate for a pulverized fixed. Flue gas	62.5/58.3	2142/8640^3	C/D
r stoker furnace m for a separate, uel ratio is fixed.	75.5/71.3	2619/10890^3	C/D
re blown into and of the conventional, not fixed.	0-60/0-60	0-2278/0-9650^3	C-A/D-A

B

C

I-1

HARACTERISTICS OF
GENERATOR DESIGNS
100 TO 500 MW

ble Furnace Input from 0/500 MW),	Design Waste Rate Corresponding to Frac. Waste Heat Input (100/500 MW), tpd	Steam Conditions[1] Corresponding to Frac. Waste Heat Input (100/500 MW)	Refuse Disposal Cost Range,[2,3] $/Ton
0-60	0-2278/0-9650[3]	C-A/D-A	2. 50-4. 90
0-60	0-2278/0-9650[3]	C-A/D-A	1. 80-4. 70
. 6/ . 9	317-500/1364-3408	C/D	0. 50 (credit)-8. 00
8. 3	2142/8640[3]	C/D	0. 30-2. 00
1. 3	2619/10890[3]	C/D	2. 40-3. 20
-60	0-2278/0-9650[3]	C-A/D-A	3. 80-7. 60

a

TABLE I-1 C

Candidate	System Description	Permiss Frac. Hea Refuse (1 $
Case 7	Shredded refuse is fired by the spreader stoker principle in a furnace also equipped with pulverized coal burners. Fuel ratio is not fixed.	0-60/0-60
Case 8	Shredded refuse and pulverized coal are fired in suspension in a common furnace in a manner that will induce slagging. Fuel ratio is limited.	0-40/0-40
Case 9	Shredded refuse and pulverized coal are fired in suspension in a common arch furnace. Fuel ratio is not fixed.	0-60/0-60
Case 10	Shredded refuse is fired in suspension in a separate arch furnace to generate partially superheated steam for a pulverized-coal fired superheater. Fuel ratio is fixed. Flue gas flows are isolated.	58.0/54.5

1. The four steam conditions (throttle tem ^{o}F/Reheated Steam temperature, ^{o}F) o

   A. 850/900/no reheat
   B. 1250/950/no reheat
   C. 1800/1000/1000
   D. 2400/1000/1000

   Steam generator efficiency and, thus, f by both steam conditions and refuse rat

2. For systems capable of firing over a w (Cases 1, 2, 6, 7, 8, and 9), a minimu input from refuse was designated.

3. In the cost analysis, an arbitrary uppe for refuse firing rates.

4. Arbitrary upper limit specified to redu

5. System rejected after preliminary cost disposal cost.

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13

ble Furnace t Input from 0/500 MW),	Design Waste Rate Corresponding to Frac. Waste Heat Input (100/500 MW), tpd	Steam Conditions[1] Corresponding to Frac. Waste Heat Input (100/500 MW)	Refuse Disposal Cost Range,[2,3] $/Ton
	0-2278/0-9650[3]	C-A/D-A	2.50-5.90
4	0-1458/0-6825	C-B/D-B	3.00-6.00
	0-2278/0-9650[3]	C-A/D-A	Note 5
	1780/7450	C/D	2.10-4.60

perature, psig/throttle temperature,
bserved in this study were:

el requirement are influenced
e.

ide range of refuse inputs
m of 20% fractional heat

limit of 8000 tpd was observed

ce probability of slag solidification.

analysis because of high refuse

Detailed calculations were made in order to estimate the expected performance characteristics of the many configurations. These were developed at several levels of electrical output and over a broad range of fuel ratios, except where design constraints imposed restrictions on the proportions of fuels that could be used.

Construction costs were next generated for the many candidate designs. The new construction types were then analyzed to establish cost-effectiveness.

b. Economic Model

A detailed cost model was developed to evaluate the large number of potential combined firing systems, to determine the sensitivity of disposal costs to various cost and design parameters, and to identify the most cost optimum new plant configurations to select for detailed cost studies. This approach was not applicable to the retrofit systems because specific, existing plants were examined. Even here, however, portions of the model could be and were applied to generate needed cost information.

In general, it was felt that no single new-plant candidate would be uniquely preferred over all others because local conditions and constraints could limit the usefulness of any one system. In order to evaluate these effects, the cost model specifically analyzed the condition for two municipalities to determine the degree to which different systems would be optimum in different locations. These derivations were based on cost information valid as of July 1969. Although all costs have increased significantly since that time, the refuse disposal cost - a primary criterion of cost effectiveness in this analysis - will not have changed commensurately or necessarily even in the same direction. This is because the cost of refuse disposal with energy recovery increases with the capital, operating, and maintenance costs of a fixed system but decreases with rises in the costs of the fossil fuels that are being displaced. For systems that are inherently cost-effective to begin with, it can be generalized that, for systems designed to fire coal, the two effects will have about cancelled each other during the period since July 1969. This would not be true of steam generator designs based on the combination firing of refuse with oil or natural gas that now burn, respectively, low sulfur oil or liquified natural gas. Such systems, although not specifically examined in this study, would clearly have benefitted greatly since July 1969 in having a portion of such fuels displaced by refuse.

The cost model developed for this program (discussed in detail in Section III. C and Appendix C) was incorporated into a detailed computer program to facilitate the analysis of the large number of design options. The model was based on the primary assumption that the power companies using refuse as a fossil fuel substitute would be regulated public utilities with privately owned equity financing the subject to all applicable Federal, state, and local taxes. This and other basic assumptions resulted in a fixed charge annualization rate average of 14.7 percent. This should be compared to a typical annualization rate of 7.3 percent for municipal ownership and perhaps 20 percent for unregulated commercial ownership. The annualization rate for utilities was, however, observed in all of the cost analyses performed.

In computing costs it was assumed that the combined firing plant would operate in a base load condition at an 80 percent plant factor; a high plant factor is indispensable for the support of refuse disposal operations. In addition, a value (subsequently much exceeded) of $.31/10^6 Btu was used as the cost of fossil fuel replaced by refuse.

One of the most important parameters in determining the net cost of disposal using a combined firing process is the value of the power generated in the plant. In this analysis, values in the range of 6 to 8 mills/kwh were used depending on the electrical power generating capacity of the plant and the cost of fossil fuel.

The cost model examined plants with power generating capacities in the range of 100 to 500 MW with from 20 to 60 percent of the input heating value derived from refuse. Nominally, refuse was assumed to have a heating value of 4460 Btu/lb (based on 1965 data) compared to 12,020 Btu/lb for coal. The combined firing plants handled from 500 to 5500 tpd of refuse, depending on the electrical power capacity, the refuse fraction, and the plant configuration.

A sensitivity analysis was conducted to determine the effect of selected variations in the economic and design parameters, such as plant factor, refuse heating value, coal cost, and rate of return on capital investment. It was found that the net disposal cost tends to be a very sensitive value, primarily because it is computed by taking the difference of two rather large numbers, operating costs and the credit for power generated. Small percentage changes in these numbers effect large changes in the absolute value of the difference.

c. Detailed Design and Cost Studies

(1) New Plants

The capital and operating expense of grinding refuse had a dominating influence on the disposal costs for the various designs analyzed. Those candidates employing agitating grates wherein only oversized input items would have to be reduced were generally found to be the more cost-effective. Within this class, a configuration designated as Case 3, clearly emerged as an optimum design for the unit size-range (200-400 MW) best suited to utility and waste management operations in large metropolitan areas.

Despite indicated higher disposal costs, a candidate was also selected from the class of designs specifying suspension firing. This was done because, lacking any data from precedent refuse-firings, conservative performance characteristics had to be assumed for these systems, and because refuse-grinding costs needed further verification for similar reasons. The system selected from this class, designated as Case 10, was seen in the cost modeling to be optimum for that type of design. Summary descriptions of the two class-optimum candidates follow:

(a) Steam Generator with Refuse-Fired Economizer (Case 3)

The Case 3 steam generator design resembles, in basic lay-out, a widely regarded combined-fired boiler now in operation in Germany (Munich South, Unit No. 6). The two differ significantly, however, in several major features, as will be brought out later.

At the sizing (400 MW) shown by the cost model to be optimal, the Case 3 system comprises a pulverized-coal fueled boiler equipped with very little economizer surface but otherwise of conventional design, and three refuse-fired furnaces that would serve as the actual economizers. These feedwater heaters would burn about 930 tpd of refuse on reciprocating grates and deliver feedwater slightly below saturation (657°F and 2600 psig) to the "economizer" (actually a mixer) of the steam generator. The latter, firing about 3000 tpd of pulverized coal, would produce about 2.8×10^6 lb/hr of steam at 1000°F and 2400 psig for a single turbine-generator set equipped for reheat operation. The net plant heat rate would be about 10,100 Btu/kw-hr.

The flue gas from the economizers would be intrinsically isolated from that of the steam generator. Thus the flue gas exiting from all three economizers would be combined, passed through an electrostatic precipitator, without concern for SO_2 removal, and on to a common plant stack. In the coal-fired boiler, the flue gas would be passed through a limestone wet-scrubber to remove SO_2 and particulates and thence to the common stack.

Based on the cost model criteria discussed earlier and a net plant refuse rate of 2790 tpd (25% of the energy input), the total net disposal cost would be \$1.61 per ton. This figure includes, however, a transportation cost of \$1.65, showing that the plant itself would operate at a profit of \$0.04 per ton. Thus refuse disposal using this particular design would not only be competitive with but considerably more cost-effective than landfill.

(b) Steam Generator with Refuse-Fired Arch Furnace (Case 10)

The system selected from among the suspension-fired designs as being the most cost-effective would incorporate a refuse-fired arch furnace. In this unit, ground refuse would tend to burn in suspension because of the mode of injection and reaction to the lifting effect of directional air flow. Water-cooled grate bars would be installed on the sloping walls of the hopper to provide some retention of fallout. The need for this feature is highly uncertain and its omission would greatly reduce construction costs.

In the total plant system, 1960 tpd of refuse (60% of total energy) would be fired in conjunction with 496 tpd of coal. A single arch furnace would fire all of the refuse in combination with 182 tpd of pulverized coal, the latter to insure even combustion. This unit would produce 0.8×10^6 lb/hr of steam at 750°F and 1940 psig. The steam would be fed to a coal-fired (164 tpd) superheater of special design, where it would be brought to final turbine inlet conditions (1000°F and 1800 psig). A single turbine would be needed to satisfy the design goal of 100 MW.

Because of tube-surface distribution constraints, reheat for the turbine would be accomplished in a second coal-fired (150 tpd) furnace rather than in the superheater. On the fire side, the two coal-fired systems would be almost identical. A number of design differences would be necessary for the steam side, however. Controls for such a system would necessarily be more complex than for conventional steam generators.

As pointed out earlier, the disposal costs for the suspension-fired systems were found to be higher than for grate-fired configurations. In the present case, the estimate came to $6.17 per ton, including transportation costs. The accuracy of this value is much less certain than for the more straightforward Case 3 situation. Not only might the performance specifications, but grinding costs as well, prove overly conservative.

The data available for developing the latter were quite limited and tended to be inconsistent. The grinding costs used for the present design (2-in. top size) were about $2.50 per ton, including annualization of capital costs, and operating and maintenance costs.

(2) Retrofit Plants

(a) Background

The plans developed for retrofit opportunities were based on examples of existing, utility-class boilers that had gone into service in the earlier part of the past two decades. Within this class of older boilers, only the more typical designs and steam conditions were considered.

Five retrofit designs were prepared for unit nameplate ratings ranging from 44 to 300 MW. In each case, the design was so developed that the original unit capacity and steam conditions were not changed.

(b) Design Summary

Modification No. 1. The selected 60 MW unit (no reheat capability) firing pulverized coal from horizontally-aligned guns would be retrofitted with a reciprocating grate. Extensive changes in the steam circuitry in the lower portion of the furnace were indicated, as was the addition of new air-supply equipment. The modified unit would derive 43% of its energy from refuse (951 tpd) and produce, as before, a steam output of 0.6×10^6 lb/hr at 900 psig and 900°F.

Modification No. 2. In this design, a separate, refuse-firing furnace, equipped with reciprocating grate, would be added onto an existing 150 MW unit and the two furnaces coupled to share the existing convection and downstream flue structure. It is assumed, of course, that sufficient space is available at the site to permit such an expansion. This retrofit system would generate 1.1×10^6 lb/hr of steam at 2035 psig and 1053°F, using a reheat cycle. About 24% of the energy would be derived from refuse, based on a rate of 1000 tpd. Because of the add-on boiler effect, the cost of this particular modification proved to be much higher than for any other retrofit system considered. The resulting unit would be similar in function to boilers now in operation in Munich and Stuttgart.

Modification No. 3. This retrofit design would involve a restructuring operation similar to that specified for Modification No. 1. The grate installed, however, would be of the travelling type. Air-swept spouts would be installed above the grate for introducing shredded (4-in. top size) refuse into the furnace; thus, a spreader-stoker configuration would be realized. This 44 MW unit would generate 0.4×10^6 lb/hr of steam at 1370 psig and 905°F. About 50% of the energy would be derived from refuse (846 tpd).

Modification No. 4. This design was based on the use of the same existing plant just considered for Modification No. 3. The boiler would, however, be equipped with a reciprocating grate and operate in much the same manner as Modification No. 1. The basic difference between the latter and the present system would be in the styles of construction of the existing boilers and therefore the modification techniques necessary to achieve conversion. The existing plant considered for Modification No. 1 was a much older plant than the present one, such that considerably different approaches would be necessary to produce what would essentially be the same result.

The present design calls for firing of 679 tpd of refuse, which would represent 42% of the heat input.

Modification No. 5. This design involves the modification of one of the units at a midwestern power plant where a similar retrofit is already being pursued under EPA sponsorship. In the present case, suspension firing would also be practiced using refuse nozzles that would be wall-mounted above existing, horizontally-aligned coal guns. A notable difference would be the conversion of the hopper walls to provide a water-cooled grate surface. Being steeply sloped, this surface would only have a delaying effect on, but thus promote more complete burn-out of, fallout tumbling into the ash pit. This conservative design feature may prove unnecessary, in which case a major modification cost-element could be eliminated.

The hopper-wall treatment of the present retrofit system, that of Case 6, which is identical in principle, and that of the arch furnace (new construction, Case 10) are very similar and provide no horizontal retaining-surface. Thus the completeness of particle combustion while in suspension is an important consideration in determining the refuse fraction to be used. Burn-out in an arch furnace is expected to be more complete because of furnace-air distribution. For this reason, a lower refuse fraction has been stipulated for the present system.

Based on a conservative fractional heat input from refuse of 10%, this 300 MW unit would consume 635 tpd of that fuel. Steam production would be about 2.3×10^6 lb/hr at 2,200 psig and 1010°F, using a reheat cycle.

(c) Disposal Costs of Retrofit Systems

A different approach than that used for the new construction units was necessarily employed in deriving disposal costs for the retrofit designs. Annualization factors for the existing plant prior to retrofit were of course excluded, as were credits for electricity generated. Many of the cost derivations employed in the cost model were applicable, however. The results are tabulated below.

REFUSE DISPOSAL COSTS FOR RETROFIT SYSTEMS

	Mod. 1	Mod. 2	Mod. 3	Mod. 4	Mod. 5
Disposal Cost, $/ton	0.65	2.87	2.14	1.07	3.69* or 4.44

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*Lower cost results if hopper walls are not modified.

The above data again show that suspension firing (Modifications Nos. 3 and 5) leads to apparent higher disposal costs. Of the grate-stoked systems, Modification No. 2 proved to be an exception to this effect because of its very high reconstruction cost.

An important parameter that is included in the disposal costs shown above is plant factor, which was 80%. This is the same value that was applied to the new constructions designs and may prove overly optimistic considering the age of the retrofitted boilers. Disposal costs would increase about 25% for each 10% (relative) drop in plant factor until a plant factor of about 50% is reached.

3. Recommended Research and Development

a. Criteria

In the absence of a sufficiently high economic incentive, a technology typically advances at a rate determined by experience gained in the practical employment of the device or process. The rate of incorporation of advancement in such industries is slow and seldom is there a sudden acceleration in the growth cycle. Designs remain conservative in order to minimize economic risks of sales. The industry in effect stagnates even though its product might potentially offer great advantages over alternative methods or equipment. Only through a properly programmed research and development effort can the true worth of a technology be established.

In the last several years, innovations for superior incineration of solid wastes have begun to be studied, but clearly the industry has largely found the support of an adequate R&D program to be unwarranted on economic grounds, and utilities express a lack of interest in considering the use of refuse as a fuel. With a number of analytical studies, including the present one, demonstrating that combustion of refuse can offer significant advantages under a rather wide range of conditions, research must be encouraged in this area. The establishment of the fact that incineration with energy recovery is an economically sound process in itself forms a portion of the encouragement. The outlining of a definitive 5-year program of R&D that will lead to improvements in the ability of this industry to be attractive to outside capital would also contribute towards this end. Suggested plans for such a program at two different levels of support are discussed below.

A listing of the many elements that might be considered to influence refuse combustion would be impressive in length. It would include waste generation rates, compositions, possible effects of partial salvage, numerous factors affecting the combustion process, the nature of all combustion products (and their reactions with each other and items of hardware), heat transfer considerations, energy utilization, air pollution control, and residue disposal. In order to develop a superior total system, the several disciplines of engineering and science would need to make their contributions to analysis and research of these parameters, as would economists, operations research experts, and other specialists. Viewed in this broad scope, hundreds of individual programs could be suggested, each adding to the knowledge of the incineration process. Some would improve understanding of underlying theoretical principles, others would lead to improved facility designs, and still others would improve the accuracy of existing data. While all this information would be "useful," the sum of it hardly makes up an R&D program that should be considered by the Government to encourage the use of refuse as a low sulfur fuel. Clearly it is necessary to place well-defined limits on the scope of activities if this prime objective is to be met.

Criteria considered important for incorporation of an individual R&D task into an integrated program include:

- Key information is needed in an area that would probably not receive proprietary support from industry.

- Fundamental research within the university and research institute system on the particular subject matter is not expected to be conducted with currently visible private funding during the period of concern.

- Numerous projects exist that require similar major facilities or test equipment, where sharing of a central laboratory would offer important cost savings and unification of effort.

- Information compilation, as an end to itself, is not a sufficient basis for project justification. Results, mainly obtained experimentally and in a few cases analytically, must be directly applicable to the construction and operation of facilities using refuse as a fuel in an air pollution-free manner and must encourage such a use for refuse.

Under the above criteria, a number of projects are eliminated that might be considered by some as vital to the cause of successful refuse combustion. Their elimination does not imply that the tasks are not worthy of support, but only that it is believed that (1) funding will be accomplished through sources other than the presently planned R&D program, or (2) incorporation of them here would detract from the main developmental needs of that program. Typical of such tasks are further projection of refuse generation rates, kinetics of nitric oxide formation, development of abatement processes for hydrogen chloride effluent, and investigation of byproducts from ash.

Suggested projects considered to meet the list criteria are discussed below.

b. Plan A

A time period of 5 years and a total expenditure of approximately $5 million make up the basic constraints of Plan A. Because of the high costs of suitable research equipment and test apparatus and the redundancy that would occur in the purchase of these items by individual investigators, it is recommended that a central R&D facility be established as a key feature of this plan. While not all research elements would be necessarily conducted at the central facility, it is believed that the improved quality and quantity of work that could be accomplished at this specialized laboratory would make the scheduling of most programs there highly advisable. Responsibility for administration and service of the 20,000 sq ft facility could be vested in either a contractor or the Government, with individual contractor teams then arranging for time at the laboratory.

Further description of this central facility is given in Section IV.

Of the original $5 million, approximately $3 million would remain for conducting R&D*. Areas where efforts should be concentrated, along with an estimate of costs, include:

- Experimental flow modeling of a variety of refuse burning systems in order to increase furnace efficiency and minimize design risks for new large incinerators - $400,000.

- Resolution of present uncertainties in causes of corrosion and fouling and means to decrease these phenomena - $300,000.

- Analytical studies under a single set of assumptions to ascertain comparative advantages of "non-conventional" thermal conversion systems for refuse (pyrolysis, gasification, etc.) - $200,000.

- Sub-scale component tests of innovations for both retrofit and new construction facilities - $600,000.

- Acquisition of data leading to improved air pollution control devices for particulates when refuse is burned - $500,000.

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*That some 40% of the funds allocated are required for construction, outfitting, and basic servicing of the lab should not be considered as a negative feature of this recommendation. It should be borne in mind that (1) greater expense would be incurred in equipment duplication in separate facilities, (2) contractors would desire to use the lab on a no-cost (or even would be willing to rent space) basis and hence more R&D than actually funded would be accomplished, (3) a lower overhead burden would result on contractor work assigned to the lab, and (4) the facility life would be greatly in excess of the 5-year planning period used here.

- Analytical study to establish lower quantity limit where air pollution free refuse combustion with energy recovery is economically competitive - $100,000.

- Combustion studies in versatile, well instrumented, furnace to ascertain means for improved burn-out at highest possible heat release rates - $900,000.

c. Plan B

The assumption of $25 million in funding over a five-year period is made for R&D Plan B. The same $2 million facility of Plan A should be constructed and the research conducted that was recommended in that plan; the last mentioned area above, essential to design of improved large incinerators, should be increased in funding by $2.1 million to $3 million. One of the objectives of the program will be to assist in the funding of a full scale facility, able to burn refuse in a fully practical manner, yet instrumented for extensive monitoring and designed for ease of component arrangement. This funding requirement, exclusive of the design phase, is estimated at $10 million. Other R&D areas that should be covered under the broader financial support of Plans B include:

- Experimental investigations of refuse pyrolysis and gasification, the exact nature of these tests to depend upon the analytical studies and the outcome of the limited research currently being conducted - $3 million.

- Experimental investigation of fluidized bed refuse combustion, with the aim of reduced capital cost per unit of capacity and decreased air pollution emissions - $3 million.

- Preparation of a detailed manual of retrofit construction recommendations, permitting existing utilities to begin burning refuse at minimum costs and risks - $1 million.

- Design of a 100 tpd combined fired incinerator with energy recovery, with capability of yielding practical data for optimization of future large units - $1 million.

II. REFUSE AS A FUEL

A. QUANTITIES AVAILABLE

1. Collection Rates

a. United States

(1) Current Collection Rates

In order to estimate the quantities of refuse presently collected in the U.S., the existing data, consisting of studies by metropolitan planning authorities and other miscellaneous documents, were analyzed to determine collection rates of refuse in various classifications. This material was examined to assure that as many as possible independent estimates of total refuse collected by a given population were identified. This also served as a further check on the comprehensive data obtained by questionnaire and published by the Committee on Solid Wastes of the American Public Works Association (APWA) (Ref. 1). The per capita refuse rates given in Reference 1 are for municipal refuse collected by city forces; they do not include privately-handled industrial wastes. They are, however, all based on actual weight records and are collection rates. The overall medians and ranges of values are:

1965 APWA SURVEY - COLLECTION RATES

Type	lb/cap. -day
Residential	2.0 (1.1 - 3.2)
Commercial and Industrial	2.0 (1.3 - 2.6)
All Refuse	3.9 (2.3 - 6.5)

The significant spread noted emphasizes the wide variability from city to city in actual amounts collected for municipal disposal, which may or may not reflect a similar variability in actual generation rates.

Table II-1, a summary of various surveys conducted, further illustrates the magnitude of the problem. It unfortunately also reflects the fact that a standard breakdown of the categories of solid waste had not been observed. Thus, while the tabulation appears to show wide variations, the totals do not all involve the same components. In any case, three things are apparent from this tabulation: (1) the widely used collection rates of around 4.5 lb/capita-day appear to have a basis in fact; (2) the amount of industrial waste is large and widely variable; and (3) there has been a substantial increase in the collection rate in the last 10 to 15 years. The information in column VIII is based on a study (Ref. 8) almost 20 years old. It gives the average for 13 California cities. In columns XI

TABLE II-1

SUMMARY OF REFUSE COLLECTION RATE ESTIMATES

(in pounds/capita-day)

Area:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Reference:	3	2	3	4	5	6	7	8	9	10	8	11
Year:	1967	1966	1968	1968	1967	1966	1965	1950	1961	1960	1950	1967
Residential	2.4	-	2.0	3.1	2.9	2.8	-	2.1	-	2.7	1.5	-
Commercial	1.4	-	1.0	-	0.6(1)	-	-	-	-	1.9(1)	0.7	-
Demolition and Industrial	1.4	-	1.2	-	-	2.7	-	-	-	-	-	-
Brush, Park Refuse, etc.	0.3	-	0.3	-	0.1	0.1	-	-	-	-	-	-
Sub-Total:	5.5	4.5	4.5	5.0(2)	3.6	5.8	4.0	2.1	3.9	4.6	2.2	6.0
Other	1.8	-	-	-	-	1.4	-	0.8	-	-	-	4.0
Total:	7.3	-	-	-	-	7.2	-	2.9	-	-	-	10.0
Avg. Growth (%/year)(3)	-	-	-	1.94	1.00	2.00	2.62	-	1.06	1.69	-	2.50

Footnotes:

(1) Includes industrial
(2) Balance of refuse from unspecified sources
(3) Projected average growth rates

AREAS

I. Various
II. Chicago, Illinois
III. Various
IV. Various

V. Malden, Massachusetts
VI. Boston, Massachusetts
VII. San Francisco Bay Area, Calif.
VIII. Thirteen California Cities

IX. Boston, Massachusetts
X. Milwaukee, Wisconsin
XI. Fresno, California
XII. Fresno, California

and XII, the Reference 8 data for Fresno are compared with 1967 data. A 6% per annum increase is indicated; this apparent large increase in collection rate probably reflects in part a more complete acquisition of data in the later study. Where the data permit, the rates of increase from the other listings have been calculated and are given. The references cited were chosen because they presented new data or estimates for the particular area concerned and did not merely repeat collection rates from previous work.

These data represent year-around averages, as was required for the present study. It was noted in examining the individual sources that the per capita refuse collection rates varied depending on the season of the year, and that the amount of variation depended on the climate of the locality.

The data presented in Table II-1 and those from other sources were analyzed by the EPA*. This agency then published (Ref. 12) preliminary refuse collection figures for the national situation based on extrapolations involving some 45% of the population. These data are shown in the following table.

ESTIMATED AVERAGE SOLID WASTES COLLECTED
(pounds/capita-day)

Solid Wastes	Urban	Rural	National
Household	1.26	0.72	1.14
Commercial	0.46	0.11	0.38
Combined	2.63	2.60	2.63
Industrial	0.65	0.37	0.59
Demolition, Construction	0.23	0.02	0.18
Street and Alley	0.11	0.03	0.09
Miscellaneous	0.38	0.08	0.31
Totals	5.72	3.93	5.32

Because industrial and demolition/construction wastes do not usually find their way into the collection system used for handling mixed municipal (urban) refuse, a per capita value of 4.8 lb/day appears to be a reasonable reference point. In the present study, however, the base year from which projections were established was 1965. The above survey data was collected several years later and thus includes a small increase due to increased per capita generation rate. It was felt therefore than an arbitrary adjustment to conform with the frequently used 4.5 lb/cap.-day rate would be acceptable.

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*Various organizational name changes have occurred during the last 4 years within Federal agencies concerned with environmental problems. Throughout the report, other than in the reference listings, all groups currently within the Environmental Protection Agency will be referred to as EPA, rather than by the name assigned at the time.

This value, incidentally, is also in reasonable agreement with a more recent estimate (4.0 lb/cap.-day) published by A. D. Little Co. workers (Ref. 13) involved on an EPA program related to the present one.

This collection rate multiplied by the population of the United States gives the total quantity of mixed municipal refuse available in the U.S. For the years 1964 and 1966, the population was estimated (Ref. 14) by the Bureau of Census as 194,583,000 and 196,842,000, respectively. At the base point year for the study, the population would have been about 195 million people. This furnishes, as a preliminary value, a refuse output for the Nation of about 160 million tons for the year 1965.

(2) Projected Collection Rates

The future increase in the collection of mixed municipal refuse will be a function of the national population growth and the urban waste produced per capita.

The Census Bureau is projecting the population of the country through 1990 on the basis of four estimates of completed fertility or gross reproduction rate. The maximum fertility rate used corresponds approximately to that for the U.S. in the 1962 to 1965 period, as it is expected that the birth rate will decline. For the purposes of this study, the data in Reference 14 were smoothed; a probable intermediate value was then estimated and extrapolated to the year 2000. The maximum and minimum estimates at the year 2000 proved to be no more than 10% different from the probable intermediate value, which has been used for this study. It reflects an intermediate level of fertility decrease during the next 30 years and involves an average annual growth rate for the period of 1.52%. These estimates are shown in the following table.

PROJECTED U.S. POPULATION
(Millions of People)

Year	Minimum	Most Probable	Maximum
1965	-	195	-
1970	205	207	209
1975	215	221	228
1980	228	238	250
1985	242	257	275
1990	256	278	300
1995	273	301	330
2000	293	326	361

In projecting the refuse collection rates per capita, the assumption may be made that the portion of the gross national product (GNP) devoted to personal consumption expenditures is a reasonable measure of the rate of collection of solid waste.

In the following tabulation, data from Reference 15 have been used to calculate the mean annual percentage growth rate of several components of the GNP. These data are per capita, in constant (1958) dollars, so that their growth rates should be measures of individual consumption of real goods requiring ultimate disposal.

RECENT GROWTH IN CERTAIN GNP ELEMENTS

	Value, Constant Dollars per Capita				Mean Rate of Increase %/Yr		
	1950	1960	1964	1967	1950-67	1960-67	1964-67
Gross National Product	2342	2699	3025	3361	2.15	3.19	3.58
Personal Consumption Expenditures	1520	1749	1945	2160	2.09	3.06	3.56
Durable Goods	229	248	307	362	2.74	5.55	5.65
Non-Durable Goods	752	828	886	969	1.51	2.28	3.03
Services	539	673	752	829	2.57	3.02	3.30

In applying these data to the present projections, it is clear that the increase in the per capita consumption of non-durable goods has the greatest bearing on the future dimensions of urban refuse resources. As shown in Section II, A, 2, products from this classification must constitute the bulk inputs that go to form the typical compositions of mixed municipal refuse. Constituents arising from non-manufactured sources, e.g., garden wastes, are also important and are probably not undergoing a per capita production increase in view of the growing trend to apartment habitation. This factor suggests that conservatism be observed in estimating the rate of increase of per capita urban refuse production based on GNP indicators.

As seen in the above table, the increase in the per capita consumption of non-durable goods was about 1.50% per year for the period 1950 to 1967. This period included cycles of both economic recession and growth, and is thus reasonably representative.

On the basis of the foregoing considerations, it was decided that an annual growth of 1.5% in quantity of mixed municipal refuse (collected) per capita be assumed as the most probable.

The oncoming era, however, may well see an even stronger trend in the marketing of shorter-lived non-durables and of disposable items previously of the durable class. The arbitrary higher rates of 2.0 and 2.5% were therefore also included in the calculations. On projecting these rates of increase for a growing population from the base date to the year 2000, the urban refuse collection quantities shown in Table II-2 result.

TABLE II-2

ESTIMATES OF FUTURE URBAN REFUSE COLLECTIONS IN THE U.S.

Year	Probable U.S. Population, Millions of People	Urban Refuse Collected						
		Lb/cap.-day			Annual rate of increase per capita	Nationwide, 10^6 tons/yr		
		1.5%*	2.0%	2.5%		1.5%*	2.0%	2.5%
1965	195	4.50	4.50	4.50		160	160	160
1970	207	4.85	4.97	5.09		183	188	192
1975	221	5.22	5.49	5.76		211	221	232
1980	238	5.63	6.06	6.52		245	263	283
1985	257	6.06	6.69	7.37		284	314	346
1990	278	6.53	7.38	8.34		331	374	423
1995	301	7.03	8.15	9.44		386	448	519
2000	326	7.58	9.00	10.68		451	535	635

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*Probable rate

b. Selected Metropolitan Areas

In order that the present program would be aligned to specific rather than generalized application opportunities, six large metropolitan areas (LMA's) were selected for closer scrutiny. The selection was logically based on the SO_2 problem operating in the various LMA's and the availability of a population density and urban configuration that would be conducive to refuse disposal by the method considered herein.

The listing of cities in Table II-3 includes all those credited with severe or very severe (rating 4 or 5 on an arbitrary scale of 1 to 5) SO_2 pollution problems in Reference 16. That document summarizes more detailed data from the NASN, CAMP and cooperating state and local networks (for example, Ref. 17) and serves the desired purpose of pinpointing those cities with SO_2 pollution problems. Also indicated are the ratings for total suspended particulate matter on the same arbitrary scale of 1 to 5. These SO_2 pollution ratings are of greater value for this task than the actual numerical data, as they include effects of topography, meteorology, density and location of sources, and intensity and distribution of days with high SO_2 (even if only on a qualitative basis). The last column gives the 1965 population (Ref. 14) of the associated Standard Metropolitan Statistical Area (SMSA).

From Table II-3 the cities underlined were selected as having solid waste pollution problems, having substantial background data available, and having different enough characteristics to make their inclusion in the study worthwhile. Several cities were excluded for reasons not apparent from the table. Newark posed uncertainties in the projection of future growth and the direction of change; East Chicago-Gary suffers more from SO_2 pollution from industrial activity than from power generation; the same is probably true of Jackson, Seattle, and El Paso. From among the remaining three smaller metropolitan areas (New Haven, Wilmington, and Providence) which are similar in terms of the parameters of interest, New Haven was selected.

In order to predict the quantity of refuse that will be collected in the selected LMA's, data was obtained and/or examined from the following sources:

- Regional Planning Agency of South Central Connecticut, Private Communication
- "The Next Twenty Years," The Port of New York Authority, August 1966.
- Greater Philadelphia Chamber of Commerce, Private Communication
- Chamber of Commerce of Metropolitan St. Louis, Private Communication

TABLE II-3

LARGE METROPOLITAN AREAS HAVING SEVERE SO_2 POLLUTION PROBLEMS

Core City	Rating SO_2 Pollution	Rating Total Suspended Particulates	SMSA 1965 Population (Thousands)
New Haven, Conn.	5	3	704
Wilmington, Del.	5	5	468
Washington, D. C.	4	3	2,408
Chicago, Ill.	5	5	6,689
East Chicago, Ind.	5	5	596
Indianapolis, Ind.	4	5	984
Covington, Ky.	4	4	1,347*
Baltimore, Md.	5	5	1,854
Boston, Mass.	5	4	3,205
Jackson, Miss.	4	2	137
St. Louis, Mo.	5	5	2,249
Newark, N.J.	5	4	1,851
New York, N.Y.	5	5	11,366
Cleveland, Ohio	5	4	2,000
Youngstown, Ohio	4	5	523
Philadelphia, Pa.	5	5	4,664
Pittsburgh, Pa.	4	5	2,372
Providence, R. I.	5	4	739
El Paso, Tex.	4	5	344
Seattle, Wash.	4	2	1,179

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*Cincinnati SMSA.

Note: Underlined cities discussed in text.

- Abstract of "Metropolitan Populations to 1985: Trial Projections," Rand Corporation
- "Statistical Abstracts of the U.S.," various years.

From these data populations projections were made, as shown in Table II-4. It can be seen that a considerable difference in growth rate is anticipated for the various cities and for the individual cities themselves over the period of the projection.

Projections of the refuse collected in each of the selected LMA's are presented in Table II-5. These data are based on the population predictions shown in Table II-4, an average collection rate per capita-day of 4.5 lb as of the base year of 1965, and an increase in per capita urban-refuse collections of 1.5, 2.0, and 2.5% per year over the entire period 1965 to 2000. In comparing the refuse quantities produced by the 6 LMA's (Table II-5) for the years 1965 and 2000, it can be seen that the smallest predicted increase will entail a factor of 2.4. This is for the estimated slowest growing LMA (New York) when using the lowest per capita increase in refuse collection (1.5%). The greatest increase factor is 5.6. This is for the predicted fastest growing LMA (Washington, D. C.) when using the highest per capita increase in refuse collection (2.5%).

2. Refuse Composition

a. Analysis of Current Refuse

Information on the composition of refuse is quite limited, although the work of J. M. Bell and associates at Purdue (Ref. 18 and 19, and others), is notable for its completeness. Kaiser (Ref. 20 and 21) has taken data such as Bell's on the proximate analysis of refuse, and has gone on to provide heats of combustion of the various components or classes of materials found in refuse. The composition and combustion properties of the refuse hence can be determined readily by computation once the given refuse has been hand-sorted to determine the proportions of the components.

The refuse compositional breakdown used for the present work was based on an averaging of data given by Kaiser in Ref. 22 and by EPA's Daniels in a private communication (Ref. 23). The latter document included data compilations from nine other sources. The percentages shown in the following table can be considered to represent values for the year 1965.

TABLE II-4

POPULATION PROJECTION FOR SIX SELECTED CITIES

LMA	Year - Population in Thousands				
	1965	1970	1980	1990	2000
Chicago, Ill.	6,820	7,500 (1.91)	9,200 (2.04)	11,140 (1.93)	14,200 (2.45)
New Haven, Conn.	490	545 (2.15)	660 (1.93)	750 (1.29)	820 (0.90)
New York, N. Y.	11,300	11,900 (1.04)	13,000 (0.78)	14,500 (0.80)	16,000 (0.99)
Philadelphia, Pa.	4,660	5,090 (1.78)	6,030 (1.70)	7,160 (1.73)	8,550 (1.79)
St. Louis, Mo.-Ill.	2,260	2,470 (1.79)	2,980 (1.89)	3,670 (2.11)	4,500 (2.06)
Washington, D. C.	2,300	2,620 (2.64)	3,380 (2.54)	4,300 (2.44)	5,500 (2.49)

NOTE: Average annual percent growth for each period is shown in parenthesis.

TABLE II-5

PROJECTED QUANTITIES OF REFUSE COLLECTED IN SIX SELECTED CITIES

LMA	Refuse Rate Increase per cap., %*	Refuse Collected, 10^3 tpd				
		1965	1970	1980	1990	2000
Chicago, Ill.	1.5	15.3	18.2	25.9	33.1	53.8
	2.0	15.3	18.6	27.9	37.4	63.9
	2.5	15.3	19.1	30.0	42.3	75.8
New Haven, Conn.	1.5	1.1	1.3	1.9	2.4	3.1
	2.0	1.1	1.4	2.0	2.8	3.7
	2.5	1.1	1.4	2.2	3.1	4.4
New York, N.Y.	1.5	25.4	28.9	36.6	47.3	60.6
	2.0	25.4	29.6	39.4	53.5	72.0
	2.5	25.4	30.3	42.4	60.5	85.4
Philadelphia, Pa.	1.5	10.5	12.3	17.0	23.4	32.4
	2.0	10.5	12.6	18.3	26.4	38.5
	2.5	10.5	13.0	19.7	29.9	45.7
St. Louis, Mo.-Ill.	1.5	5.1	6.0	8.4	12.0	17.1
	2.0	5.1	6.1	9.0	13.5	20.3
	2.5	5.1	6.3	9.7	15.3	24.0
Washington, D.C.	1.5	5.2	6.4	9.5	14.0	20.8
	2.0	5.2	6.5	10.3	15.9	24.8
	2.5	5.2	6.7	11.0	17.9	29.4

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*Probable rate = 1.5%

ESTIMATED COMPOSITION OF MIXED MUNICIPAL REFUSE

Refuse	Mean Weight-% (as received)
Garbage	20
Garden Wastes	12
Plastics	2
Glass	12
Metals	10
Paper Products	38
Residual (rags, paint, wood, etc.)	6

b. Projected Composition

The development of estimates describing the future trend in the compositions of mixed municipal refuse was necessarily based on very limited information. It was therefore necessary to make certain assumptions and accept rates of change for specific components which had been predicted by other workers (e.g., Refs. 24 and 25). From these bases, equations were then derived for each class of constituent. These are shown in Table II-6 and the results of their application to the data contained in the above table are shown in Figure II-1.

c. Seasonal Variation

An equation was fit to the data in Reference 26 to predict the seasonal variation in the total residential (household) solid waste. The equation is:

$$f_T = -0.01 - 0.051 \cos\left(\frac{\pi}{6} N\right) + 0.021 \cos\left(\frac{\pi}{3} N\right) + 0.008 \cos\left(\frac{\pi}{2} N\right)$$

$$-0.003 \sin\left(\frac{\pi}{6} N\right) - 0.02 \sin\left(\frac{\pi}{3} N\right) + 0.01 \sin\left(\frac{\pi}{2} N\right) \qquad \text{(II-1)}$$

where

f_T = percent change from the mean

N = months.

The total residential refuse for a given month then is

$$W_{TR} = \overline{W}_{TR} (1 + f_T)$$

where

$\overline{W}_{TR}$ = the mean residential waste collected, lb/cap.-day.

TABLE II-6

PROJECTED COMPOSITIONAL CHANGES IN MIXED MUNICIPAL WASTES

Constituent	Equation	Basis
Garbage	$f_G = f'_G \exp(-0.0034\ N)$	Ref. 24 - data extracted is for refuse collected in Berkeley, California, from 1952 to 1967.
Plastics	$f_{PL} = f'_{PL} \exp(0.0052\ N)$	Ref. 25.
Glass	$f_{GL} = f'_{GL} - \frac{f'_{PL}}{2} \exp(0.0052\ N) + \frac{f'_{PL}}{2}$	It is assumed that the fraction of glass will be reduced by one-half the increase in the fraction of plastics.
Metals	$f_M = f'_M - \frac{f'_{PL}}{2} \exp(0.0052\ N) + \frac{f'_{PL}}{2}$	It is assumed that the fraction of metals will be reduced by one-half the increase in the fraction of plastics.
Plants and Grass	$f_{PG} = f'_{PG}$	It is assumed that there will be no change in the fraction of plants and grass.
Residual	$f_R = f'_R$	It is assumed there will be no change in the fraction of residual.
Paper	$f_{PA} = 1 - f'_G \exp(-0.0034\ N) - f'_{GL} - f'_M - f'_{PG} - f'_{PL} - f'_R$	The fraction of paper is calculated to obtain a balance

where

N = number of months

f_{XX} = as received fraction of the particular waste

f'_{XX} = as received fraction in 1965.

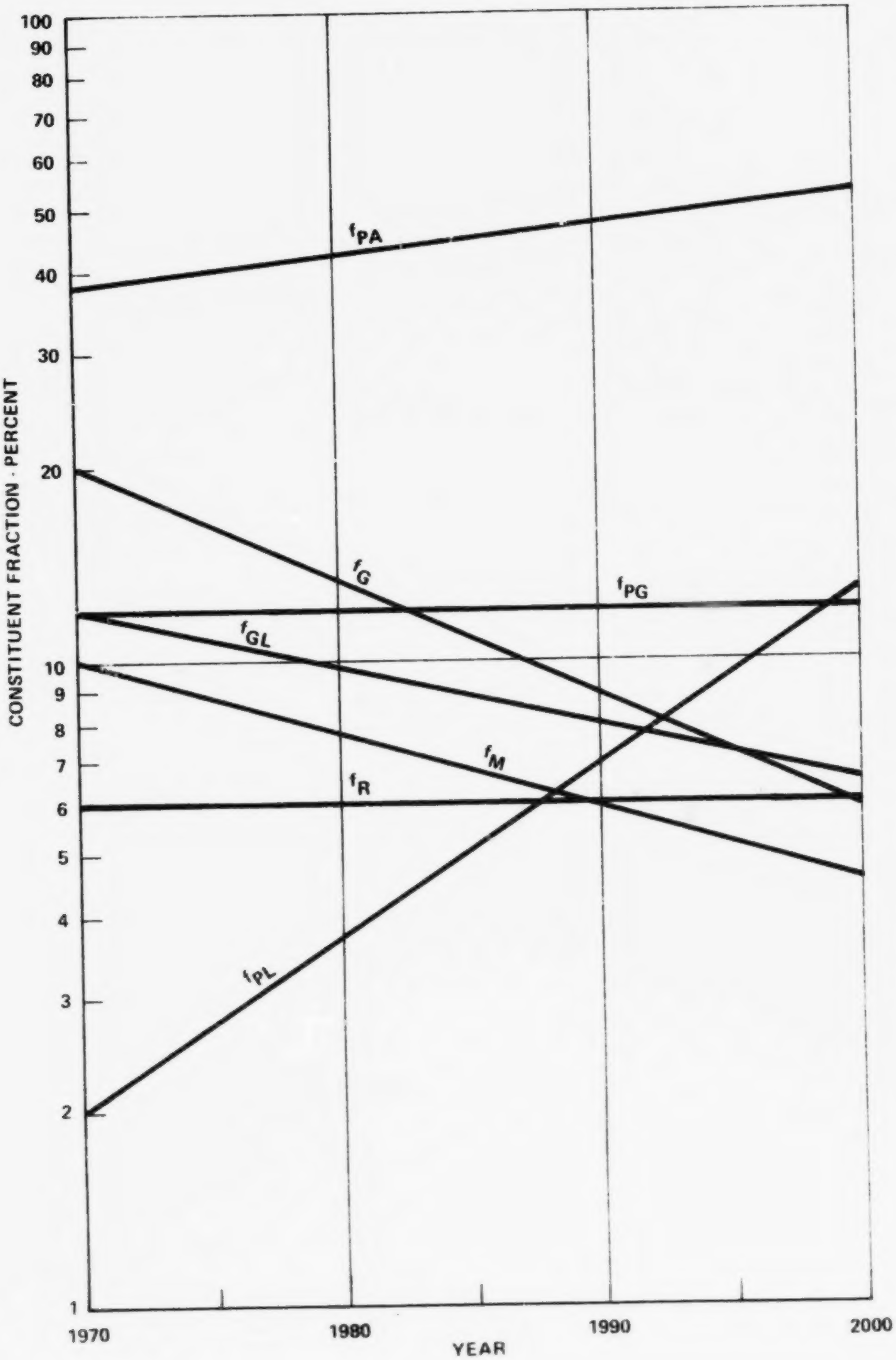

FIGURE II-1. PROJECTED COMPOSITIONAL CHANGES OF MIXED MUNICIPAL REFUSE

The method used to generate Equation II-1 was to fit curves to segments of the data and them combine them using the Fourier series. The equation for obtaining $\overline{W}_{TR}$ was the same as that used to derive the waste load projections in Table II-5; that is, for a 1.5% per capita-year refuse collection increase,

$$\overline{W}_{TR} = W'_{TR} \exp (0.00125\ N)$$

where

W'_{TR} = total as-received residential waste load in 1965, lb/cap.-day.

Assuming the balance, (IC)*, of the mixed municipal refuse load does not vary seasonally, the total solid waste load becomes

$$W_T = \overline{W}_{TR} (1 + f_T) + W_{IC}$$

$$W_{IC} = W'_{IC} \exp (0.00125\ N)$$

$$W_T = W'_{TR} \exp (0.00125\ N) (1 + f_T) + W'_{IC} \exp (0.00125\ N) \quad \text{(II-2)}$$

where

W_T = total as-received solid waste load (function of time), lb/cap.-day

W_{IC} = total as-received non-household solid waste load (function of time), lb/cap.-day

W'_{IC} = total as-received non-household solid waste load in 1965, lb/cap.-day.

Using Equation II-1, computer data were obtained to determine the seasonal variation in waste load. The results are shown in Figure II-2.

d. Heat Value

As the percentages of the various constituents in residential waste vary with time (seasonally and secularly), so will the average heating value. Data were not available to determine the seasonal variation of each constituent; therefore, for the present work it was assumed that the seasonal variation in the total residential waste load would be due to the seasonal variation in plants and grass. The following expressions can then be considered:

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*Includes commercial, some industrial, street and alley litter, and miscellaneous.

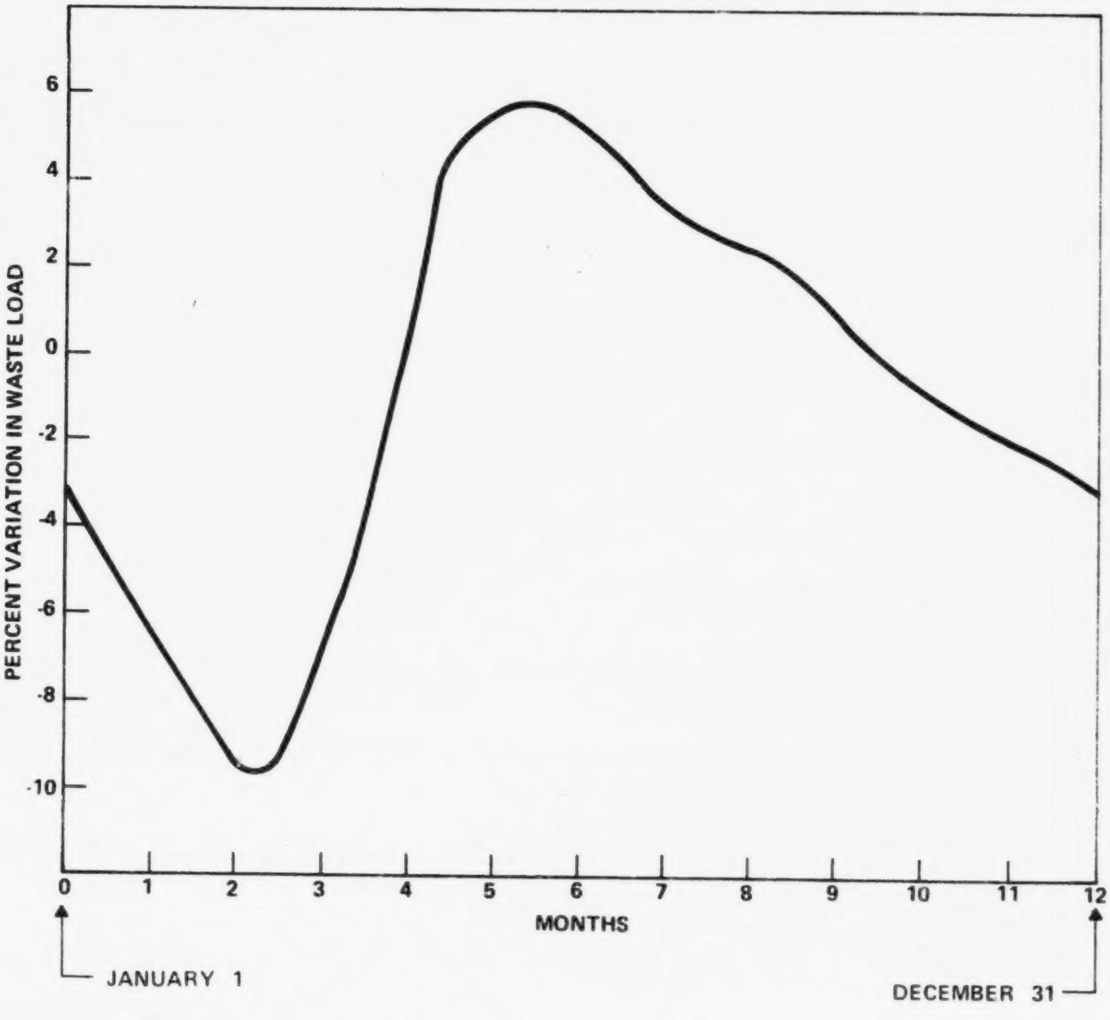

FIGURE II-2. SEASONAL VARIATION IN WASTE LOAD

$$f_{GS} = \frac{f_G}{1 + f_T}$$

$$f_{PLS} = \frac{f_{PL}}{1 + f_T}$$

$$f_{GLS} = \frac{f_{GL}}{1 + f_T}$$

$$f_{MS} = \frac{f_M}{1 + f_T}$$

$$f_{PGS} = \frac{f_{PG} + f_T}{1 + f_T}$$

$$f_{RS} = \frac{f_R}{1 + f_T}$$

$$f_{PAS} = \frac{f_{PA}}{1 + f_T}$$

where

f_{XXS} = seasonal variation in the fraction of a given waste.

Since the constituent fractions must sum to 1:

$$W'_{TR} \exp (0.00125\ N)\ (1 + f_T) = W'_{TR} \exp (0.00125\ N)\ (1 + f_T) \left[f_{GS} + f_{PLS} + f_{GSL} + f_{PGS} + f_{RS} + f_{PAS}\right]$$

Applying the equations for constituent seasonal variation and introducing a heat value,

$$\bar{h}\, W_T = W'_{TR} \exp (0.00125\ N)\ f_G h_G + f_{PL} h_{PL} + f_{GL} + f_M h_M + (f_{PG} + f_T)\, h_{PG} + f_R h_R + f_{PA} h_{PA} + W'_{IC} \exp (0.00125\ N)\ h_{IC}$$

where

$\bar{h}$ = mean heat value for solid waste on an as-received basis, Btu/lb.

By introducing the moisture and ash fraction for each constituent, heat value on a moisture and ash-free basis is obtained.

$$\begin{aligned}\bar{h}_{MAF} W_{TMAF} = W'_{TR} \exp(0.00125) \Big\{ & f_G \left[1 - (M_G + A_G)\right] h_{GMAF} + \\ & f_{PL} \left[1 - (M_{PL} + A_{PL})\right] h_{PLMAF} + f_{GL} \left[1 - (M_{GL} + \right. \\ & \left. A_{GL})\right] h_{GLMAF} + f_M \left[1 - (M_M + A_M)\right] h_{MMAF} + \\ & (f_{PG} + f_T) \left[1 - (M_{PG} + A_{PG})\right] h_{PGMAF} + f_R \left[1 - (MR + \right. \\ & \left. A_R)\right] h_{RMAF} + f_{PA} \left[1 - (M_{PA} + A_{PA})\right] h_{PAMAF} \Big\} + \\ & W'_{IC} \exp(0.00125\ N) \left[1 - (M_{IC} + A_{IC})\right] h_{ICMAF}\end{aligned}$$

where

$\bar{h}_{MAF}$ = mean heat value on a moisture and ash free (MAF) basis, Btu/lb

M_{XX} = moisture fraction of a given constituent

A_{XX} = ash fraction of a given constituent

Applying the equations shown in Table IIA-6 for secular time variation and defining $\beta_{XX} = M_{XX} + A_{XX}$:

$$\bar{h}_{MAF} = \frac{\begin{aligned} & W'_{TR} \exp(0.00125\ N) \Big\{ (1 - \beta_{PA})\ h_{PAMAF} \left[- f'_G \exp(-0.0034\ N) - f'_{PL} - \right. \\ & \left. f'_M - f'_{GL} - f'_{PG} - f'_R + 1 \right] + (1 - \beta_G)\ h_{CMAF}\ f'_G \exp(-0.0034\ N) + \\ & (1 - \beta_{GL})\ h_{GLMAF}\ f'_{GL} + \left[(1 - \beta_{PL})\ h_{PLMAF} - (1 - \beta_M) \frac{hMMAF}{2} - (1 - \beta_{GL}) \right. \\ & \left. \frac{hGLMAF}{2} \right] \left[f'_{PL} \exp(0.0052\ N) \right] + \left[(1 - \beta_M) \frac{hMMAF}{2} + (1 - \beta_{GL}) \frac{hGLMAF}{2} \right] \\ & \left[f'_{PL} \right] + \left[(1 - \beta_M)\ h_{MMAF} \right] f'_M + (1 - \beta_{PG})\ h_{PGMAF}\ (f'_{PG} + f_T) + (1 - \beta_R) \\ & h_{RMAF}\ f'_R \Big\} + (1 - \beta_{IC})\ h_{ICMAF}\ W'_{IC} \exp(0.00125\ N) \end{aligned}}{W_{TMAF}} \qquad \text{(II-3)}$$

where

$\bar{h}_{XXMAF}$ = heat value of the particular waste on a moisture and ash free basis, Btu/lb

β_{XX} = the sum of the moisture fraction and ash fraction in the particular component of waste

Any known residential waste fraction, such as those shown in the table at the end of Section IIA, 2, a, and seasonal variation, such as Equation II-1, can be applied to Equation II-3. A value for non-household waste load is tabulated in Section IIA, 1, a. The remaining unknowns in Equation II-3 are the respective heat values, moisture content, and ash content. Based on data from References 22 and 23, average heat values, moisture content, and ash content were estimated as shown in the following table. The data are later converted into ultimate analysis form in Section III, B, where steam generator energy balances are considered.

ESTIMATED HEAT, MOISTURE, AND ASH
CONTENT OF DOMESTIC REFUSE

	Btu/lb MAF	Percent Moisture	Percent Ash
Garbage	9,300	70	2
Plastics	14,800	0	0
Plants and Grass	9,000	70	2
Residual	7,000	15	2
Paper Products	8,500	5	15
Metals	Inert		
Glass	Inert		

Not shown in the above table are the values for the non-household class of urban refuse; this was assumed to be 8500 Btu/lb (MAF) and 20% each in moisture and ash, as suggested by References 22 and 23.

Using the values of the above table, Equation II-3 was solved to yield the change in heating values, $\bar{h}_{MAF}$, from the year 1970 to 2000. The results are shown in Figure II-3. Computer data based on Equation II-1 were obtained for the years 1970 and 1971 to show the seasonal variation in heat value. A plot showing the seasonal variation of the as-received and MAF heating value is shown in Figure II-4 for the two-year period. The variation is only about ±2% on the as-received basis and insignificant on the MAF basis. It will be noted that the two minima in Figure II-4 occur at about the same times (July and August) as the maximum for waste load shown in Figure II-2. The latter is largely due to seasonal variation in garden waste collections. An increase in the content of high moisture garden waste in refuse would tend of course to depress the heating value, but not in direct proportion.

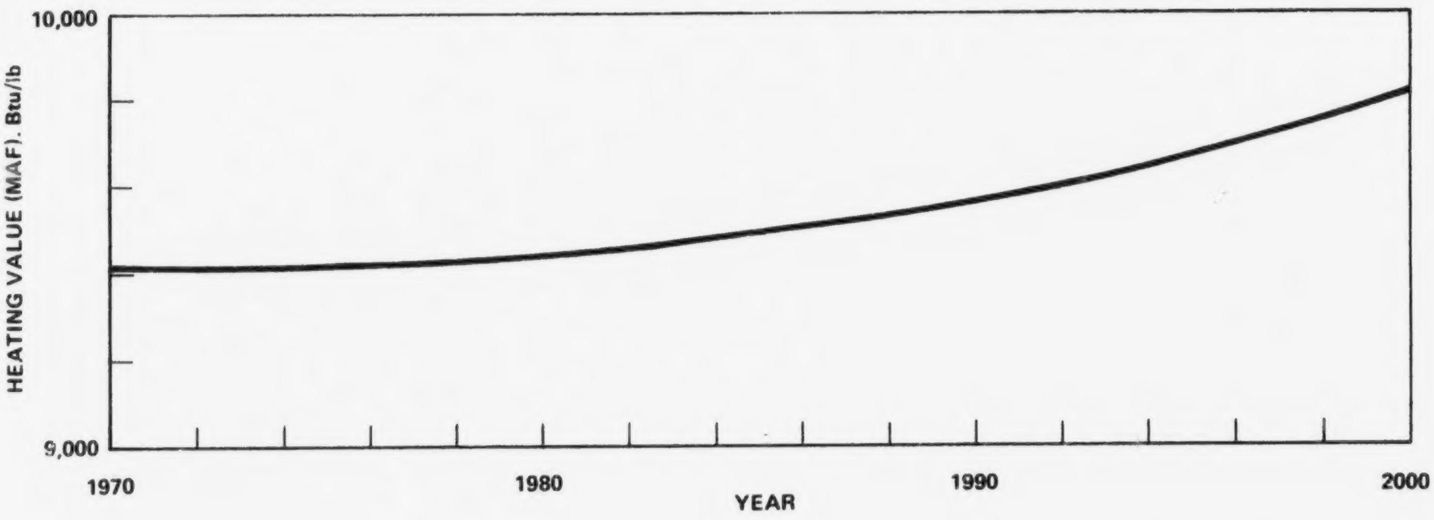

FIGURE II-3. PROJECTED HEATING VALUE OF MIXED MUNICIPAL REFUSE
(MOISTURE AND ASH FREE)

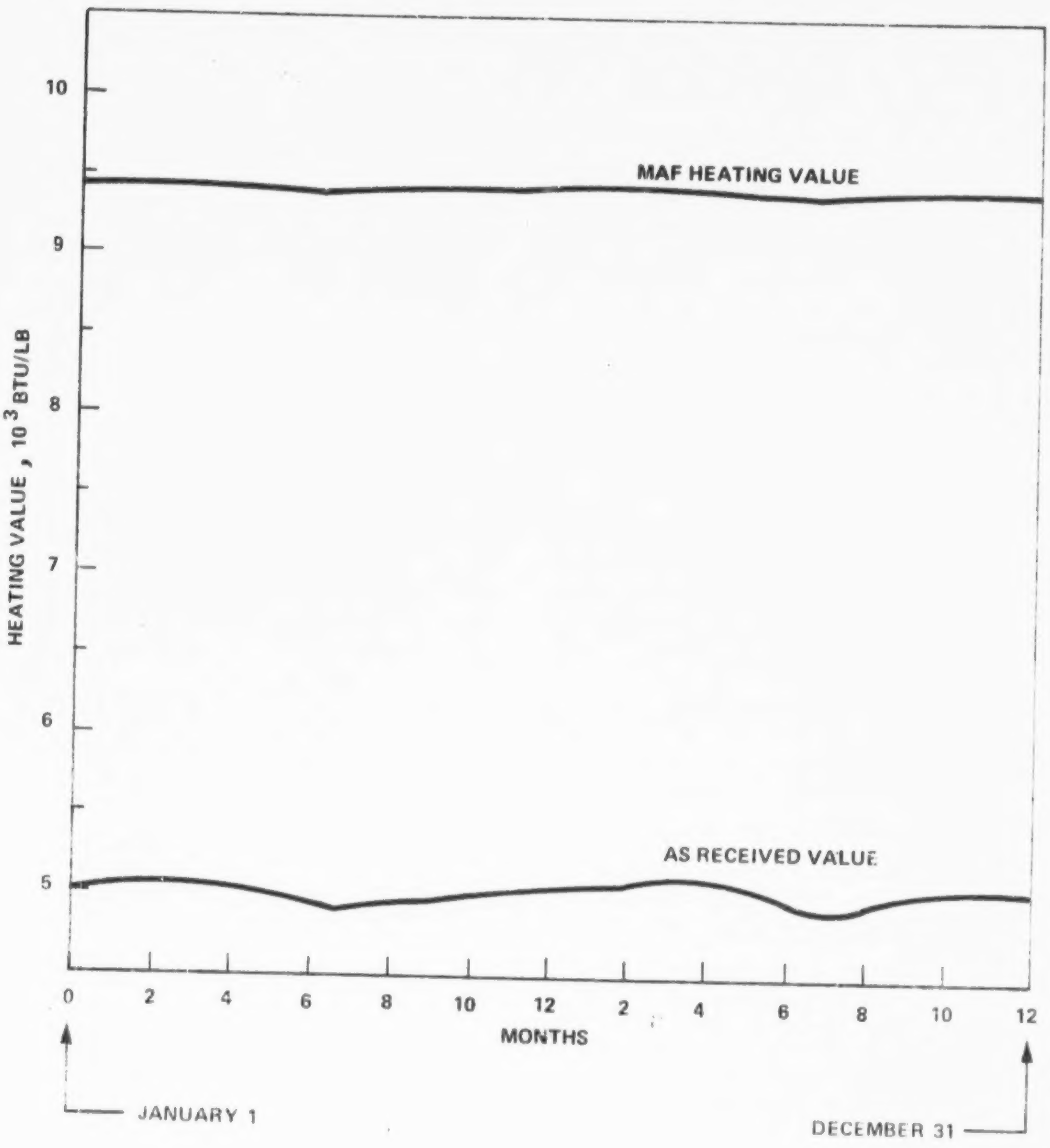

FIGURE II-4. SEASONAL VARIATION IN HEATING VALUE

The information considered in the present section (II.A) will have an important bearing on the projections developed in Section II.C. These concern the potential pollutant reductions that can be expected by using mixed municipal refuse to replace a portion of the fossil fuel fired in power plants.

B. COMBUSTION AND INTERACTIONS

1. Introduction

Refuse is a readily combustible fuel much like other fuels widely used in furnaces and steam boilers, however much its handling before combustion may differ. It can be and is being burned (principally in Europe) with or without auxiliary fossil fuel in water-walled furnaces to generate high pressure, superheated steam, without excessive corrosion or other problems. There is no reason that it could not be so burned in the United States.

There is no evidence for interactions between refuse and fossil fuel combustion products. In particular, there is no evidence that sulfur oxides from fossil fuels are absorbed by ash from refuse. There is good evidence, however, that even under efficient firing conditions only a small portion (15 to 30%) of the sulfur in refuse appears in the flue gas, contrasted to about 98% for fossil fuels; it is probable that fixed sulfur in the refuse (e.g., $CaSO_4$ from gypsum wall board) accounts for this fact, which is observed both in the U.S. and in Germany.

Refuse is at present burned on stirring-type grates of a style long obsolescent for utility combustion of coal, and experience with its firing in suspension is just now becoming available. The conclusion of no interaction drawn above should remain valid for the suspension firing of refuse.

There is good evidence that refuse exhibits greater ash fouling tendencies than most U.S. coals, and means for avoiding this problem, both in design of new plants and operation of modified plants, must be considered.

The properties of combustion products of combinations of refuse and fossil fuel, the possible interactions and compatibility of these products, and any possible synergistic effects on pollutant emissions are important parameters to examine in the initial phases of any solid waste combustion study. The proximate analyses of refuse vary widely (cf. Section II.A above) with the variations as great among samples delivered to the same incinerator as from region to region. However, the ultimate analyses are much less variable and the heats of combustion even less so. As a fuel, refuse is much more variable than familiar fossil or other waste fuels, yet reasonably consistent in overall composition of combustion products. There is a wide variation in ash compositions, as there is in coals, but where the ash of a coal from a given mine is reasonably constant in composition, that from refuse varies from hour to hour.

2. Gaseous Combustion Products

a. Major Products

In a competently designed and operated furnace, refuse burns to the same ultimate combustion products as do fossil fuels, as indicated in the following tabulation:

REFUSE COMBUSTION PRODUCTS

Refuse Component	Major Combustion Product Gaseous	 Solid
C	CO_2	
H	H_2O	
O	CO_2 and H_2O	
Moisture	H_2O	
N	N_2 (+ NO and NO_2)	
S	SO_2 (+ SO_3)	$CaSO_4$, etc.
Cl	HCl	NaCl, etc.
Other minor	Various	Various
Ash		Ash
Metal		Metal plus oxide
Glass and ceramics		Unchanged

The amount of carbon monoxide in the oxygen-containing boiler exit gases is negligible. Its equilibrium concentration at typical furnace exit temperatures of 2100 to 2300°F with 10% or more excess air is under 8 ppm (Ref. 27, Table I). Equilibrium concentration at the adiabatic flame temperature may be some thousands of ppm, and values at the flame front in small flames may be up to 100 times that at equilibrium, as they are in laboratory hydrocarbon-air flames (Ref. 27, Figure 4). Reaction kinetics are sufficiently rapid, however, for the carbon monoxide level to reach close to the low equilibrium values mentioned above as the gas cools to furnace exit temperatures (Ref. 27, Appendix A-2) in large furnaces.

Carbon monoxide is a contributor to corrosion (see I, D, 1, Appendix A) in areas where hot, under-oxidized, combustion gases contact bare metal; that is, of course, especially troublesome where the metal is boiler tubing under pressure. Thus, good design assures either that adequate amounts of combustion air are thoroughly mixed with the burning refuse, or that the water walls or boiler tubes in the part of the furnace affected are covered with protective refractory. This problem is particularly acute in grate-fired incinerators burning untreated, mixed refuse, because of its variability. Suspension firing will allow adequate mixing and will thereby permit operation with lower overall percentages of excess air.

During combustion, combined hydrogen in the refuse converts completely to water, as it does with fossil fuels. Again, as with carbon monoxide, the factors of excess air, residence times, and furnace exit temperatures are such that no elemental hydrogen is found in the combustion gases leaving the furnace, regardless of what species exist in the high temperature flame zone.

Oxygen in the organic part of refuse fuel will appear in the flue gas as H_2O or CO_2; its fate, as distinguished from that of the oxygen in the combustion air, is unimportant. It is of course important insofar as it determines combustion air requirements and heat of combustion. The large oxygen content of refuse, primarily from the cellulosic constituents, contributes both to the lower heating value and to the low theoretical air requirement for refuse. In terms of pounds of gas per unit of heating value, the quantities of either combustion air or wet flue gas are about the same as for coal, however. This is shown in the following table, the basic data of which are explained or developed in Section III, B.

COMBUSTION CONSTANTS FOR REFUSE AND COAL

	lb air/ lb fuel	lb flue gas/ lb fuel	HHV Btu/lb	lb air/ 10^6 Btu	lb flue gas/ 10^6 Btu
Refuse, stoichiometric	3.20	4.02	4,460	717	903
Coal, stoichiometric	9.75	10.77	12,022	810	894

b. Pollutants

(1) Nitrogen

Bound nitrogen in fuels appears to be burned almost entirely to elemental nitrogen, although recent information indicates the concentration of nitrogen in fossil fuels does somewhat affect nitrogen oxides (NO_x) levels in combustion gases (Ref. 28 and 29). These oxides are primarily formed from nitrogen and the free oxygen in the flue gas, the amount being determined by the concentration of oxygen from excess air, the maximum temperatures in the flame zone, the temperature-time history of the gases as they cool, and possibly other as yet unrecognized factors. Within the furnace, nitrogen is first fixed as NO; with excess oxygen present, a small portion of the NO is then oxidized to NO_2 during the cooling, the amount again depending upon the form of the cooling rate curve (Ref. 30). From a theoretical point of view, one would expect the concentration of NO_x from a conventional well-run refractory incinerator to be very much lower than those from the refuse portion of a combined-firing boiler installation. This is because the very high excess air of the former, and resultant low flame temperatures, should have a depressing effect on their formation. However, comparative data in the literature suggest only factors in the range of 1.5 to 4, on the rational basis of pounds of NO_x per million Btu:

NO_x EMISSIONS FROM VARIOUS TYPES OF FURNACES

	Nitrogen Oxides		
	Ref.	lb/ton fuel	lb/10^6 Btu
Municipal Incinerator	31	2	(0.25)*
Average Incinerator	32	3.03	0.34
Water Walled Incinerator Suspension Firing	32	3.44**	0.39**
Coal Fired Boilers	31	20	(0.76)*
Coal Fired Boilers	33		
Vertical		-	0.55
Corner Fired		-	0.71
Front Wall		-	0.95
Spreader Stoker		-	0.76
Cyclone		-	2.20
Horizontal Opposed		-	0.59

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*Derived value.

**Estimate.

Refuse burned under the higher temperature conditions of a water-walled boiler, especially in a combined furnace with fossil fuel, should give concentrations of nitrogen oxides comparable to those from the same weight of fossil fuel. This does not mean, however, that an increase in total nitrogen oxide burden to the atmosphere would occur on switching from conventional incineration to firing the refuse in steam generators. The latter would involve a reduction in the amount of fossil fuel fired and thus in the amount of NO_x emissions, even though the emissions from the refuse portion had increased. The reduction in NO_x emissions would be roughly equal to the percent of fossil fuel displaced divided by the factor by which the NO_x emissions from refuse had become increased in changing from incinerator to boiler firing. Thus a 10% displacement of coal by refuse would result in a 2.5% to 6% reduction in total NO_x, based on the range of 4 to 1.5, discussed above, for the NO_x increase factor for refuse. Similarly, no increase in NO_x emissions would be involved for the case of landfill vs steam generation. The NO_x output from power plants would be about the same whether refuse were fired or not.

(2) Sulfur

(a) Background

Sulfur is, of course, of major concern. Economic fossil fuels (except natural gas which has limited availability) are all relatively high in sulfur content, and probably above 98% (Ref. 31) of the sulfur appears in the flue gas as sulfur dioxide with small, but not unimportant, amounts of sulfur trioxide (Ref. 33). It is of course one of the major goals of this program to evaluate the potential reduction in sulfur pollution by the substitution of refuse for fossil fuels in power generation.

U.S. refuse is truly a low-sulfur fuel, averaging between 0.1 and 0.2% sulfur overall (Refs. 13, 31, 33, 34). One investigator (Ref. 35) has measured flue gas concentrations from municipal incinerators in New York City averaging the equivalent of 0.29% sulfur in the fuel if it all appears in the flue gas. Individual measurements ranged from 0.096 to 0.487%, typical of the variability commonly observed in refuse analyses. Furthermore, half or more of the sulfur appeared as sulfuric acid in all cases. This is a distinct difference from other observations (Refs. 33, 36-38) in which the SO_3 is 1 to 3% of the SO_2, in coal, oil, refuse, and combined firing plants.

With the single exception of Reference 35, the sources cited agree on from less than 0.1 to 0.2% sulfur in municipal refuse in the U.S. Kaiser (Ref. 33) has postulated that a substantial fraction (ca 75%) of the sulfur in refuse remains in the residue and fly ash, in contrast to coal. He suggested that refuse ash is sufficiently basic and reactive to absorb appreciable quantities of sulfur dioxide from the flue gases. If this were the case, there is the possibility of a synergistic effect in the combined firing of refuse and high sulfur fossil fuel to reduce the sulfur oxides emission below that corresponding to a simple addition of the emissions from the two fuels. It is considered highly unlikely that such effect would be of any great significance in reducing sulfur emissions from boiler plants. The reasons are:

1. The wide variability in refuse bottom ash and fly ash composition would prevent continuous effective results.

2. The ranges of composition of refuse ash, combined-firing ash, and coal ash are so similar that there is little likelihood of a substantial difference in behavior as to SO_2 absorption (see the following discussion).

3. Proper combustion of refuse will expose the fly ash to the high flame temperatures characteristic of good fossil fuel-fired utility furnaces, which will tend to overburn it and deactivate any absorptive properties it may have. Hence, any synergistic effect is expected to be small.

4. Control of sulfur oxide emissions from utility plants will eventually require 10 to 20-fold reductions in emission. Any small synergistic effect of burning up to 50% (on a heat basis) of refuse would still require a sulfur removal system, whose cost would be more heavily influenced by the volume of flue gas to be treated than by the initial sulfur oxide level. Substantial reductions in capital cost for sulfur removal equipment are possible in several combined firing systems examined in this study, in which the flue gases are kept separate until after treatment. This arrangement, of course, precludes any synergistic effect.

(b) European and U.S. Data

In Europe, the amounts of fly ash from grate burning of refuse and from pulverized coal firing are comparable. Although the largest portion (ca 85%) of the non-combustibles in the refuse appear as grate residue, the amount of fly ash is still substantial because of the generally much higher non-combustible content of European refuse than coal. This is partly due to the presence of significant quantities of coal ash (from domestic space heaters), a characteristic not typical of U.S. refuse. Analysis of the TÜV data reveals that fly ash carry-over on grate firing of refuse is in the same range as the total ash content of coals; that is, 3 to 6% of the total fuel feed. There will thus be more fly ash per Btu from refuse than from coal by a factor of approximately three*. Examples of the magnitudes are given in the following table:

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*As explained in Section II, C, this ratio does not apply in this country.

FLY ASH FROM REFUSE AND COAL COMBUSTION

Installation	Type of Firing	Fuel, lb/hr Refuse	Fuel, lb/hr Fossil	Grate Residue lb/hr	Fly Ash lb/hr	Fly Ash % of Fuel
Düsseldorf (Ref. 36)	Refuse only	23,100	-	7,350	1,100	4.8
Munich North 1 (Ref. 38)	Test 1, coal only	-	25,200	-	1,550	6.2
Munich North 1 (Ref. 38)	Test 5, coal and refuse	59,300	15,400	21,800	4,080	5.5
Stuttgart No. 28 (Ref. 37)	Test 4, oil and refuse	53,000	12,080	12,500	1,590	2.4

Since the amounts of reactant added in the various limestone and dolomite SO_2 removal processes are comparable in magnitude with the fly ash from coal, the contacting efficiency of ash and SO_2 should be potentially adequate for some reaction; with suspension firing of ground refuse, undoubtedly a greater fraction of fly ash will result. However, dry absorption SO_2-removal processes in general have efficiencies less than 50% (Refs. 39, 40), even with injection of a properly activated, 100% reactive, agent into a low temperature area of the furnace to prevent deactivation. Refuse fly ash is substantially the same as coal fly ash, except for its much wider short-term variability and a tendency toward higher alkali and sulfur content on the average (see Table II-7 and Refs. 33 and 41). The fly ash samples on which the analyses of Table II-7 were performed were in part collected for this study (the "A" series) and in part provided by A. D. Little, who had performed some particle size analyses, but no chemical analyses (Ref. 13). To be noted are (1) the strikingly high sulfate content of the two refuse-only samples (Düsseldorf, Sample 7B, and New York, Sample 1B) compared with the coal only and the combined firing samples; (2) their general similarity despite one being European and one U.S.; and (3) (except for sulfur) the similarity of all the coal, combined and refuse-only ashes. These values can be contrasted with the ones reported by Kaiser (Ref. 33) for New York incinerators examined earlier than 1964, which are summarized in the following, each column being the average of four to seven analyses:

TABLE II-7. ULTIMATE ANALYSES OF FLY ASH SAMPLES FROM REFUSE AND COMBINED FIRING INSTALLATIONS

	COAL ONLY	COMBINED FIRING				REFUSE ONLY		
		75% Coal	80% Coal	Composite	65% Oil			
	Munich North 1A Sample #1A	Munich North 1B Sample #3A	Munich North II Sample #5A	Munich North II Inlet Hopper Sample #5B	Stuttgart Sample #7A	Düsseldorf Inlet Hopper Sample #7B	New York Composite Hopper Sample #1B	
Silicon	23.0%	17.0%	18.0%	21.0%	15.0%	17.0%	18.0%	**Silicon**
Aluminum	14.0	11.0	12.0	13.0	10.0	12.0	6.9	**Aluminum**
Iron	3.2	4.1	6.8	7.3	22.0	3.6	3.0	**Iron**
Magnesium	1.6	1.5	1.6	1.8	1.1	1.5	1.2	**Magnesium**
Calcium	3.4	7.5	3.4	4.4	3.4	3.9	2.5	Calcium
Sodium	0.81	1.4	1.5	trace	trace	2.5	3.5	Sodium
Boron	0.013	0.013	0.013	0.063	0.013	0.023	0.029	Boron
Tin	trace	0.037	0.051	0.12	0.14	0.35	0.71	Tin
Beryllium	0.0011	0.00096	0.00097	nil	nil	nil	nil	Beryllium
Barium	0.080	0.30	0.19	0.23	0.31	0.30	0.12	Barium
Cadmium	nil	nil	nil	nil	nil	nil	0.010	Cadmium
Zinc	nil	0.41	0.63	0.86	0.83	1.2	1.9	Zinc
Phosphorus	nil	nil	nil	trace	1.0	nil	0.40	**Phosphorus**
Antimony	nil	nil	nil	nil	nil	nil	0.020	Antimony
Titanium	0.55	1.1	1.0	0.57	0.86	1.2	2.1	Titanium
Manganese	0.082	0.089	0.11	0.38	0.32	0.12	0.086	Manganese
Lead	0.083	0.14	0.15	1.5	0.087	0.85	2.5	Lead
Gallium	0.0099	0.011	0.0082	trace	trace	0.0091	0.0052	Gallium
Tungsten	nil	nil	nil	nil	0.25	nil	nil	Tungsten
Copper	0.016	0.020	0.020	0.023	0.71	0.027	0.019	Copper
Chromium	0.022	0.053	0.036	0.024	0.30	0.084	0.081	Chromium
Nickel	0.022	0.015	0.018	0.025	0.061	0.015	0.019	Nickel
Bismuth	nil	nil	nil	nil	nil	nil	trace	Bismuth
Molybdenum	nil	0.0054	trace	0.0071	0.020	0.0060	0.011	Molybdenum
Vanadium	0.016	0.014	0.011	0.0044	0.0045	0.0095	0.065	Vanadium
Zirconium	0.016	0.013	0.021	0.0022	0.0067	0.016	0.013	Zirconium
Cobalt	0.013	0.014	0.018	0.0073	0.026	0.010	0.0038	Cobalt
Yttrium	nil	trace	trace	nil	nil	nil	nil	Yttrium
Potassium	3.3	6.0	5.5	trace	nil	6.5	9.6	Potassium
Strontium	0.046	0.036	0.033	0.053	0.030	0.039	0.019	Strontium
Silver	0.00035	0.0029	0.0021	0.0034	0.0036	0.0030	0.00024	Silver
$SO_4^=$	2.06	5.09	3.62	6.93	2.45	12.28	11.91	$SO_4^=$
$SO_3^=$	0.15	0.07	0.03	0.03	0.01	0.06	0.04	$SO_3^=$

INCINERATOR FLY ASH COMPOSITIONS

	Sampled in Suspension in Hot Flue Gases	Sampled in Dust Collection Zones	Sampled from Stack Gas
Organic, %	31.0	3.9	21.1
Inorganic, %	69.0	96.1	78.9
Inorg. Fraction, %			
Si	22.1	22.8	17.1
Al	5.4	12.3	13.7
Ti	-	0.6	0.4
Fe	10.9	4.5	5.0
Ca	13.2	6.6	6.4
Mg	1.7	1.4	1.7
Na + K(as Na)	3.3	4.3	7.8
S (as $SO_4^=$)	1.4	3.6	9.1

Evidence from ash analyses for or against the large-scale absorption of sulfur oxides by refuse fly ash is not available. Thus, the observed larger sulfate content of some of the refuse-only fly ash samples is more plausibly explained as resulting from substantial quantities of inert sulfates in the refuse, such as would arise from the discard of plaster of Paris artifacts and the like. For example, the incineration of wall board will decompose the gypsum to anhydrous $CaSO_4$ (anhydrite) and steam, with the probable suspension of large amounts of finely-divided anhydrite.

Sulfur balances were derived for the five European steam generating plants surveyed. Because of the low sulfur content of the coal (averaging 0.7%) and the high sulfur content of the refuse (averaging 1.9% with a spread from 0.7% to 3.0%) fired in these European tests, the results cannot be directly applied in the U.S. The high refuse sulfur content, incidentally, should not be considered as typical for German refuse; due to the season, considerable coal ash from dwellings was present in the refuse. Some of these sulfur balances were based on samples collected at different times from the boiler under consideration or from data on a companion boiler, and to that extent are uncertain. (This is the case for the two Stuttgart combined firing tests and the refuse-only Düsseldorf test.) The eight balances reported for Munich North 1 and 2, including both the highest and the lowest refuse sulfur contents, were based upon sulfur values (for fuel, residue, fly ash, and stack gas) reported in the TÜV Boiler Test reports (Refs. 38 and 42). The sulfur balance tabulations for the five units are given in Table II-8. They may be summarized as follows:

A

TA

SULFUR BALANCES IN GERMAN

	Sulfur Analysis		Sulfur Distribution		Sulfur Analysis		Sulfur Distribution			Sulfur Analysis	
	% Wt.	ppm	lb/hr	%	% Wt.	ppm	lb/hr	%		% Wt.	ppm
Test Number	Düsseldorf Unit No. 1				Munich North Unit No. 2, Test 1					Munich North	
Refuse	0.78*		180.0	100.0	-		0	0		2.76*(1)	
Coal					0.69		516.0	100.0		0.66	
Total Input							516.0	100.0			
Flue Gas											
SO$_2$		492	53.2	29.5		483	500.4	91.9			941
SO$_3$		6	2.2	1.2		10	12.3	2.3			7
Flyash	4.25		47.0	26.0	1.32		31.6	5.8		2.68	
Residue	1.06		77.6	43.3	-		-	-		5.19	
Total Output			180.0	100.0			544.3	100.0			
Difference			0				+28.3				
Test Number	Stuttgart Unit No. 28, Test 1				Stuttgart Unit No. 28, Test 4					Stuttgart Unit	
Refuse	-		0	0	2.7*		1439.8	88.1		-	
Oil	1.25		242.5	100.0	1.6(2)		195.3	11.9		1.17	
Total Input			242.5	100.0			1635.1	100.0			
Flue Gas								Total	Refuse		
SO$_2$ (Air Heater)		-				595	(237.7)				
SO$_2$ (Refuse furnace)		-	0	0		105	20.3	1.2	1.4		-
SO$_2$ (Oil furnace)		811	242.5	100.0		945	195.3	11.9	-		742
Total			242.5	100.0			215.6	13.2	1.4		
Flyash		-	0	0	6.1		84.4	5.2	5.9		
Flyash (Deposited)		-	0	0	10.3(4)		43.2	2.6	3.0		
Residue (Dry)		-	0	0	10.4		1291.9	79.0	89.7		
Residue (Sluice Water)		-	0	0							
Total Output			242.5	100.0			1635.1	100.0	100.0		
Test Number	Munich North Unit No. 1, Test 1				Munich North Unit No. 1, Test 5					Munich North	
Refuse	-		-	-	0.67		382.7	75.7		0.70	
Coal	0.84		211.6	100.0	0.80		123.0	24.3		-	
Total Input			211.6	100.0			505.7	100.0			
Flue Gas											
SO$_2$		500	194.7	97.3		383	143.5	31.9			190
Flyash (Economizer)	0.54/1.96			0	2.26/2.68		4.6	1.0		2.40/2.88	
Flyash (Precipitator)	0.38/0.40		5.3	2.6	2.94/3.15		113.5	25.2		4.02/4.12	
Residue	-		-	-	0.76		188.0	41.8		0.6	
Bottom Ash	0.04/0.04		0.1	0.1	0.08/0.21		0.1	0.0		2.40/2.42	
Total Output			200.1	100.0			449.8	100.0			
Difference			-11.5				-55.9				

* By difference.

(1) 2.9 in TÜV report.

(2) Sulfur in oil reported as 1.1-1.5%.

(3) Value measured in Unit No. 28.

(4) Assumed from analysis of deposits from Unit No. 29.

β

ABLE II-8

REFUSE-FIRED STEAM GENERATORS

Sulfur Distribution		Sulfur Analysis		Sulfur Distribution			Sulfur Analysis		Sulfur Distribution		Sulfur Analysis		Sulfur Distribution	
lb/hr	%	% Wt.	ppm	lb/hr	%		% Wt.	ppm	lb/hr	%	% Wt.	ppm	lb/hr	%
nit No. 2, Test 5		Munich North Unit No. 2, Test 6					Munich North Unit No. 2, Test 7				Munich North Unit No. 2, Test 4			
2599.2 378.1	87.3 12.7	3.0 0.6		2602.0 338.8 2940.8	88.5 11.5 100.0		2.3 0.6		1427.0 105.6 1532.6	93.1 6.9 100.0	2.19* -		2180 0 2180	100.0 0 100.0
1082.9 7.9 75.2 1811.3 2977.3	36.4 0.3 2.5 60.8 100.0	n.m. n.m.	891 4.5	983.7 4.9	33.5 0.2		n.m. n.m.	900 7	496.3 3.8	32.4 0.2	3.61 4.81		358 11 55 1760 2184	16.4 0.5 2.5 80.6 100.0
0														
No 29, Test 1		Stuttgart Unit No. 29, Test 4												
0 230.2 230.2	0 100.0 100.0	2.1* 1.47*(2)		1018.3 198.8 1217.2	83.7 16.3 100.0									
					Total	Refuse								
- 0 230.2 230.2 0 0 0 0 230.2	- 100.0 0 0 0 0 100.0	12.2 10.3 5.5 -	n.m. 105 945(3)	- 18.7 198.9 217.6 182.5 48.1 769.0 -	1.5 16.3 17.8 15.0 4.0 63.2 - 100.0	1.9 - 1.9 17.9 4.7 75.5 - 100.0								
nit No. 1, Test 6														
402.8 0 402.8	100.0 0 100.0													
51.4 29.3 146.4 139.0 2.6 367.7	14.0 8.0 39.8 37.5 0.7 100.0													
-35.1														

Refuse Only - 15 to 30% of the input sulfur appears in the flue gas

Combined Firing - With (high-sulfur) oil, 13 to 18% of the input sulfur appears in the flue gas

With (low-sulfur) coal, 32 to 36% of the sulfur appears in the flue gas

Fossil Fuel Only - Over 92% of the input sulfur appears in the flue gas

Examination of the data for combined firing with oil (Stuttgart Unit 28, Test 4, Table II-8) reveals that the sulfur in the flue gas after mixing (SO_2 samples at the air heater) is, if anything, higher than the total emerging from the two separate furnaces. Thus there is evidence against any uptake of sulfur dioxide by refuse fly ash.

In the Munich North II combined firing tests it can be noted that the proportion of input sulfur in the flue gas is the same whether the boiler was at full, partial, or minimum load, with the same refuse rate, and with varying coal rate. Figure II-5, redrawn from Reference 38, gives the SO_2 (and HCl) concentrations in the flue gas for all seven tests of Munich North II; this figure vividly illustrates the statement above, that European results are not directly translatable to U.S. conditions; as the flue gas SO_2 concentrations are higher with combined firing or refuse only than with coal only. These data refer to dry flue gas; with moisture accounted for, the difference is not quite so large, but the trend remains. The Munich North II tests were run with high-sulfur refuse; the data of Tests 1, 5 and 6 on Munich North I (where the sulfur concentrations of coal and refuse were about the same, but the excess air for refuse-only was greater) indicate that the trend is not necessarily a consistent one.

Data on the Munich units can be used to examine the possibility of excess sulfur-absorbing activity by either refuse or coal fly ash. As will be apparent, sulfur dioxide in the flue gas is the same as or higher within the estimated errors with combined firing than would be calculated from a linear combination of the data for coal only and for refuse only, thus firmly suggesting the absence of synergistic effects. Data calculated from information in the boiler test reports (Refs. 38 and 42) was used to prepare the following tabulations which show these facts:

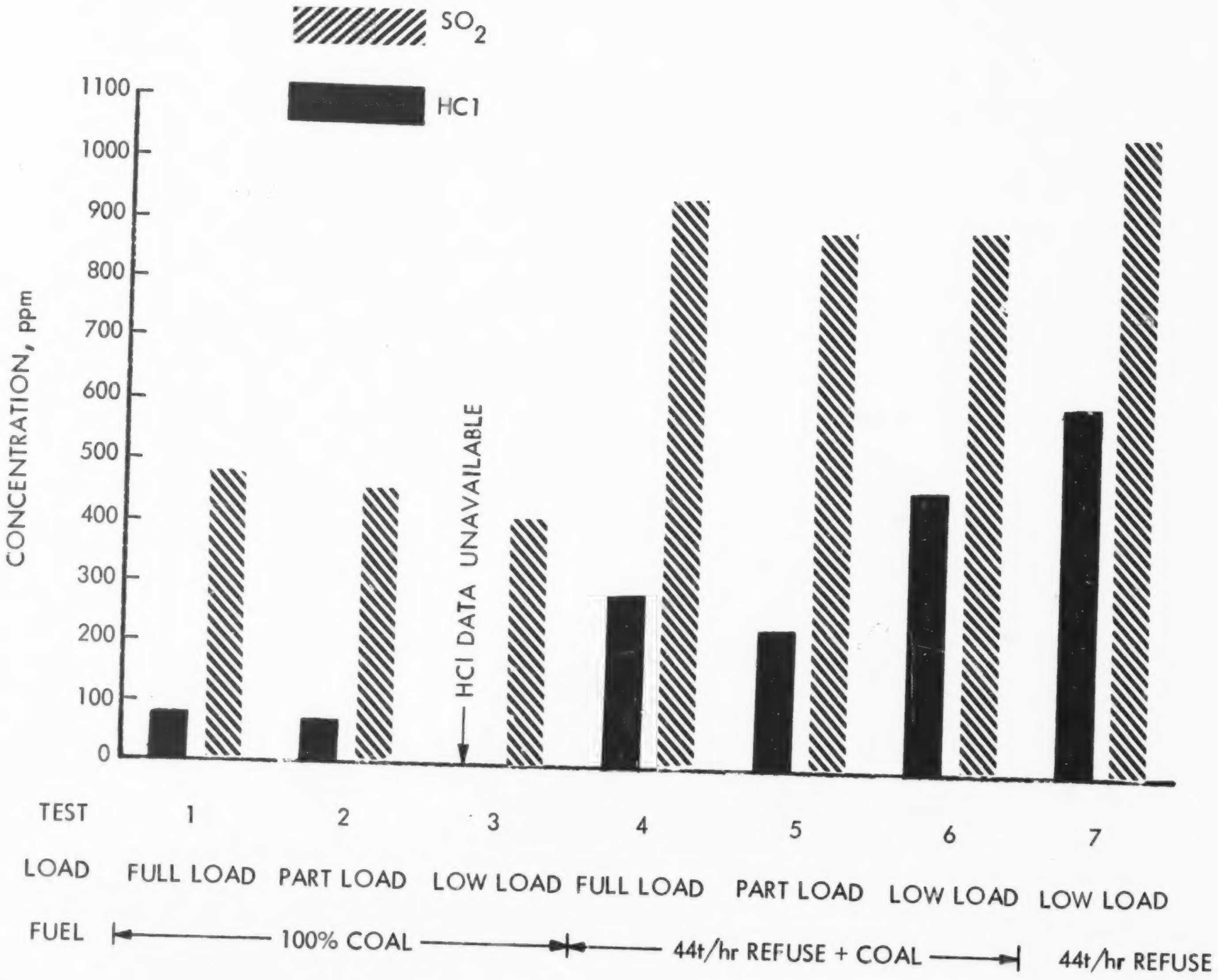

FIGURE II-5. SO$_2$ AND HCl IN DRY FLUE GAS, MUNICH NORTH II BOILER

FLUE GAS SO_2 QUANTITIES

Munich North I:

			Flue Gas S (as SO_2), lb/hr		
Test No.	Fuel	Input S (as SO_2), lb/hr	Calculated		Found
1	Coal only	212			194
5	Coal	123	112	161	143
	Refuse	382	49		
6	Refuse only	401			51

Munich North II:

			Flue Gas S (as SO_2), lb/hr		
Test No.	Fuel	Input S (as SO_2), lb/hr	Calculated		Found
1	Coal only	515			500
5	Coal	377	366	791	1083
	Refuse	2590	425		
6	Coal	338	328	753	985
	Refuse	2600	425		
7	Coal	105	102	435	495
	Refuse	1427	332		
4	Refuse only	2180			356

(3) Halides

Halides are of concern to boiler designers because of the corrosion problems associated with acidic condensates from the flue gas in the low temperature portions of the system, and postulated connections between halides and high temperature tube wall corrosion. Organic halides, from polyvinyl chloride (PVC) plastics, primarily, will burn quantitatively to HCl; inorganic halide compounds may or may not liberate HCl on combustion depending on the environment. There is some fear that increasing use of PVC plastics will cause problems of boiler corrosion as their percentage in refuse increases. So long as well-mixed municipal waste is considered, problems are not expected in the near future. The chlorine content of refuse is in the high end of the range for coals now burned, as tabulated below:

CHLORIDE CONTENTS OF REFUSE AND COAL

Sample	Reference	Cl Content, wt-% (as-received basis)
Refuse		
City of St. Louis	41	0.13, 0.15, 0.32
Atlanta, Ga.	34	0.5, 0.6, 0.3, 0.3
DeKalb County, Ga.	34	0.2, 0.4, 0.2, 0.2
73rd St. Incin, NYC*	35	0.42, 0.25, 0.13
Other NYC*	35	0.11, 0.33, 0.07
Orlando, Florida	43	
Household		0.29, 0.23, 0.24
Mixed Household-commercial		0.29
Trash		0.16
Commercial		0.63, 0.26, 0.47
Coal		
Union Elec. Co., St. Louis	41	0.03, 0.04, 0.05, 0.04, 0.29, 0.29
Various	44	0.01 to 0.46 (typical range of U.S. coals)

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*Minimum calculated from flue gas concentration of HCl.

Values of the HCl content of the flue gas were reported for six of the seven tests at Munich North II (Ref. 38). They are shown in Figure II-5 on a dry gas basis. It is seen that the values for coal only are less than 100 ppm, whereas with combined firing at full or part load, HCl values are two to three times higher, and for refuse only they are six times higher. One can calculate a minimum value for the chloride contents of the fuels from the flue gas concentrations and from the flue gas and fuel flow rates, as indicated in Table II-9.

It is apparent that the minimum chloride content of the refuse based on flue gas content is in the same range as that of most U.S. refuse chloride contents; further, the minimum chloride content of the coal is in the range for U.S. coal. The expected flue gas content of HCl from combined firing (calculated from the amounts for coal only and refuse only) is also approximately the same as that actually observed. This fact indicates no appreciable difference in absorption of HCl by fly ash from refuse and coal.

TABLE II-9

HCl EMISSIONS, MUNICH NORTH II

(Values in parenthesis are derived)

Test No.	1	2	5	6	7	4
Condition	Coal Only		Combined Firing			Refuse Only
Fuel Rate						
Coal, lb/hr	74,500	52,300	57,100	56,400	16,700	-
10^6 Btu/hr	956	685	736	730	219	-
Refuse, lb/hr	-	-	94,000	86,500	88,600	100,000
10^6 Btu/hr	-	-	254	235	235	276
Flue Gas, 10^3 SCFD/hr	13,150	9,750	15,080	14,480	7,720	4,950
Lb Flue Gas/lb Fuel	13.5	14.0	(7.1)	(7.7)	(5.6)	3.8
Excess Air, %	29	31	38	35	47	45
CO_2, %	14.40	14.15	14.10	14.10	12.60	13.20
H_2O, %	7.73	7.52	10.50	10.80	18.50	24.30
HCl in Flue Gas, Measured						
10^{-6} lb/SCFD	8.0	7.1	27.2	22.1	44.1	58.5
lb/hr	105	69	410	320	340	290
lb/10^6 Btu	0.11	0.10	0.41	0.33	0.75	1.05
Min. Cl^- in Fuel (calc.), wt-%	0.137	0.125				0.28
	0.131					
HCl in Flue Gas, Expected from:						
Coal, lb/hr			77	76	23	
Refuse, lb/hr			273	251	257	
Total, lb/hr			350	327	280	

On the rational basis of lb HCl per million Btu heat input to the boilers, the combined firing gives three to seven-fold greater HCl, and refuse gives only ten-fold greater HCl than coal only.

Other minor constituents of refuse that might be gaseous pollutants, notably lead and arsenic, would not be in the vapor phase under oxidizing conditions at boiler exit temperatures, and would be controlled to the extent suspended particulates were controlled. Their contributions to possible tube wall corrosion are discussed at length in the corrosion literature.

3. Solid Combustion Products

a. Residue

Conventional incinerators are operated primarily as tools to reduce the volume of solid waste, thus prolonging the life of the landfill. To this end, complete burnout is not necessary and many overloaded incinerators do not achieve it. When sanitation regulations specify the organic or putrescibles content of the residue, as will soon be the case universally, then complete burnout becomes more important. Electric utility companies, on the other hand, are very sensitive to fuel values in ash or clinker, and can be expected to be more concerned. From the point of view of interactions between refuse and fossil fuel combustion, it can be stated that there is no possibility of the residue on the refuse grate affecting the combustion products of powdered coal or other fossil fuels. If refuse is ground and fired partially in suspension, there is a somewhat greater possibility of interaction. Only the finely-divided material will react appreciably; this will be fly ash, and based on present analyses and observations it is not enough different from coal ash to exert any effect.

b. Fly Ash and Suspended Particulates

Discussion of possible interactive effects with examples of fly ash analyses were presented in the preceding section on sulfur oxides. One other item of importance is the organic and carbon content of fly ash. The former is of concern in relation to disposal as mentioned under residue (above), while the latter is of concern both because of its potential fuel value and its effect on electrostatic precipitator efficiency.

Heat losses due to the carry-over of organic matter or carbon in fly ash is not a serious problem with coal fired in suspension. It can be probably then assumed that the heat loss in fly ash from refuse burned on grates will also be small. This is because the fly ash from coal and refuse are quite similar and the quantities generated are roughly comparable, whether on an energy input (U.S.) or weight input (Europe) Basis.

A particular effect of combined firing of refuse and fossil fuel is that on the performance of electrostatic precipitators. This is discussed in Appendix B; in summary, though, the electrical properties of refuse fly ash are enough different from those of coal to influence the performance of electrostatic precipitators. A similar result is obtained with low-sulfur coals. Data from European combined firing incinerators with electrostatic precipitators have been instructive, but because of the much lower sulfur content of the coals used, and the higher sulfur content of refuse, the data are not directly translatable to U.S. conditions.

It appears likely that when both sulfur oxides control and particulate control are required by regulation, the cost effective solution may be a wet scrubber system adequate to remove both sulfur oxides and suspended particulates (Sec. III, B).

c. Ash Deposits and Corrosion*

A comprehensive examination of the literature on ash deposits and corrosion was made in conjunction with laboratory analyses and physical examinations of ash deposits on tubes and evaluation of their relation to corrosion in water-walled refuse and combined firing installations. The corrosion and deposit problem was brought out as a result of the publication of a series of articles in the mid 60's describing severe corrosion in the furnace and high temperature gas passes of refuse boilers (primarily the new German ones) shortly after being put in operation. The initial rather disturbing reports were followed by numerous papers which now indicate that the corrosion, although still understood only to a limited degree, has subsided or been brought under control.

As a result of detailed reviews of the literature, and discussions with operators of combined firing installations in Europe, with research personnel at Battelle Frankfurt, and with W. T. Reid, a knowledgeable U.S. authority (Ref. 45) on corrosion, the situation may be summarized as follows:

- No one in Europe really knows the exact mechanism of refuse boiler corrosion, and the proposed explanations are based upon surmise. There are several plausible theories, many, and perhaps all, of which may apply at different times.

- Corrosion in refuse boilers is mainly a nuisance at present rather than a critical problem, and poses no serious threat in Europe to existing installations. As a result, only minor attention is being given to elucidating the causes of corrosion.

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*This section summarizes the information contained in Appendix A.

The above comments should counteract the unfortunate impression, still widespread in the U. S., that high-performance, refuse fired steam generators in Europe continue to experience intolerable corrosion problems. From a design point of view, it must be acknowledged that more detailed information is desirable.

The literature can be summarized as follows:

- Corrosion takes place in the convection passes when tube metals exceed temperatures between 850 and 950°F. Corrosion, with one exception, takes place in the presence of deposits. The corrosion appears to be due to two mechanisms, one requiring a liquid phase and the other the presence of dry ash. Wickert (Ref. 46) indicates that the latter can take place under a reducing environment in the presence of K_2SO_4 in the deposit and HCl and SO_2 in the gas at the above-mentioned temperature condition. Lead is present in relatively large quantities and may be acting as an accelerator. Zinc is present in large quantities, but does not appear to be directly involved with the corrosion. It may be contributing to the deposit formation by forming a low melting phase and thereby assist in the attack.

- The presence of a reducing environment accelerates the corrosion and permits it to take place at lower temperatures. It may be an explanation for the formation of fused deposits at temperatures below the ash softening temperature of the deposits.

- Observations of corrosion in the laboratory and the field agree for the most part; H_2S is found under reducing conditions and deposits are required to be in contact with the metal surface.

- Available evidence indicates that if reducing conditions were avoided through combustion improvement, surface temperatures were reduced to 950°F, and some attempt was made to decrease the lead, potassium, and sodium fired in the refuse, corrosion problems would be minimized, if not disappear.

The conclusions from the experimental investigations performed under this contract, as well as from the literature, can be summarized as follows:

- Corrosion at high temperatures is probably due to more than one type of attack, depending upon the existence of a reducing or oxidizing situation. In either case, the corrosion appears to be strongly dependent on the existence of ash in contact with tube surfaces. Acceleration of the normally slow gas attack appears to be due to the presence of lead, sodium, and potassium. A liquid phase may be essential to promoting corrosion under oxidizing conditions, although this restriction appears not to hold under reducing conditions.

- Temperatures of 850 to 950°F appear to be the threshold range for oxidizing conditions. This temperature may drop to as low as 600°F under reducing conditions.

- Deposit problems in refuse or combined firing plants are similar to those in fossil fuel fired plants. Through careful interpretation of data, it is possible to extrapolate some of the results from one type of unit to the other. It is recommended that the total alkali (Na_2O plus K_2O, calculated as Na_2O) not exceed 0.4% by weight on a dry fuel basis, that the gas temperatures be kept low (below 950°F) in convection passes, and that reducing conditions be avoided.

- Ash deposits are formed by a diffusion of volatile minor ash constituents and inert particulate matter to the tube surface. The problem could probably be reduced by restricting lead, sodium, potassium, and zinc, in the refuse, or by diluting it with an appropriate fossil fuel. Deposit and corrosion also depend very strongly on the difference in temperature between surface and the bulk of the gas stream. Rearranging tube surface would require trading heat transfer surface for effective reduction in tube fouling. Shielded surface could be integrated into initial design of the tube bundle more effectively by considering it in advance rather than using it as a remedy.

- Even though refuse is a heterogeneous fuel, the problems appear to be the same in all boilers. Differences are probably due to variations in internal environmental conditions rather than variations in boilers or the refuse fired. With the exceptions for the effects of the presence of minor constituents such as lead and zinc, the deposits and the problems that are being encountered are similar to those encountered with coal.

- Phosphorus has been given little consideration in that it is present in small amounts. Quantities found appear to correlate with calcium concentrations. It may be partially responsible for high temperature deposits and as such should be given some attention.

- The presence of chlorine in the flue gas has been given considerable attention. Its contribution to the corrosion problem appears to be strongly dependent upon (1) the minor constituents that are present and acting as accelerators, and (2) upon reducing conditions. It appears that any contribution it makes to the corrosion problem may be overcome by controlling combustion and designing for the effect of other minor constituents present.

d. Ash Fouling Tendencies

One important criterion in the establishment of proper ratios of refuse to fossil fuel in a steam raising facility is the effect this ratio has on the maintenance costs of the heat exchange system.

Evidence was therefore sought on factors affecting ash fouling from plants now in operation so that improved design and operating practices could be suggested for the future.

It was found that the desirable proportioning of refuse and fossil fuel could not be easily defined from existing data. Chemical analyses of ash deposits from various units indicated no appreciable change in blended flue gas deposits, and it was also found that fouling was independent of total ash loading. In some European units, refractory was added to furnace waterwalls, causing an increase in furnace exit temperatures and subsequently new fouling problems on convection surfaces. Certain of the minor constituents in the ash appear to be of major importance, while chlorine, expected to be highly corrosive, was absent or seemed to play only a minor role in any deposition or corrosion phenomena.

In the combined firing of refuse and pulverized coal, it might appear that there would be some minimum coal level above which a refuse and coal mixture could still be considered a non-fouling fuel, providing that the fossil fuel was non-fouling. The recent availability of chemical analyses of raw refuse, in conjunction with experience with fossil fuels, has made it possible to propose a criterion for establishing this limit.

In designing systems for any fuel, heavy emphasis is placed on chemical analyses of the fuel. These analyses indicate not only how the fuel may be burned, but they also provide an index of potential tubeside fouling and corrosion. Previous data on refuse composition have been generally qualitative in nature and the results have often been reported by inference (Ref. 47). European experience has generally not indicated much in the way of detailed analysis, the difficulty in obtaining a representative sample being felt to be so great that additional analyses were not warranted.

The criterion proposed is based, as discussed below, on three samples of refuse taken on three different days in St. Louis, Missouri, and three samples of refuse taken on three different days in Munich, West Germany. It is suggested that a fuel is a fouling fuel when the alkali content (sodium and potassium, calculated as Na_2O) on a dry fuel basis exceeds 0.4%*. Above this value severe slagging problems are likely to be encountered on tube surfaces with metal temperatures above 950°F.

The limitation of 0.4% alkali and the temperature of 950°F is derived basically from coal and lignites; the basis of this criterion is empirical and subject to judgment. However, its basis appears to be well founded on sufficient data on bituminous coals, lignites, wood, and wood bark

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*Based upon ash analysis.

(Refs. 48, 49). The temperature limitation coincides sufficiently closely with the European experience in refuse burning that further refinement in its values is not warranted at this time. In Europe it has been found that refuse burning either by itself, or in large proportions with coal or oil, generally results in fouling where the final steam temperature is 400°C (752°F) or higher. Generally in the superheater the tube metal temperature is equal to the steam temperature plus up to 150°F.

From compositional data of St. Louis refuse in Tables No. 14 and 15 of Reference 41, Table II-10 has been prepared to show possible upper limits on refuse proportions based on the 0.4% alkali criterion. The coal chosen as the base case has the highest alkali content reported for the Meramec plant. This criterion was also applied to German data provided by Consultant Dr. M. Andritsky, with the results shown in the bottom half of the table. For the results of the application of the criterion, the heating value of the refuse was assumed as 2800 Btu/lb (HHV). The alkali content of German bituminous coal ash varies between 0.5%-5%, and for the calculation a value of 2.5% was used. The ash content of the coal was based on the analysis of the coal during the TÜV tests of the Munich North, Unit 1. The ash content was 6.4%, the moisture was 6.0% and the heating value was 13,200 Btu/lb (HHV).

The results indicate the rather wide spread that may occur in a given facility, with the St. Louis refuse having a range from 4.2 to 23% (heat input basis) and the Munich data from 1.7 to 3.7%. They furthermore suggest that the Meramec unit with 10% heat input from refuse may encounter fouling conditions, and that Munich should have. The criterion is substantiated by the experience in Munich. The mixture of refuse and pulverized coal was not expected to be non-fouling, such that ample provision was made for fouling in each of the three units. The units at Stuttgart are fired with refuse and oil, with the alkali content of the oil ash being negligible. The value for a non-fouling fuel has undoubtedly been exceeded, and Novak (Ref. 50) indeed states that they did have a substantial amount of fouling.

The suggested criterion should not be treated as a firm design rule, but it is important to recognize that it may be generally valid and thereby provide for it. This can quite easily be done for new plants. In the systems analysis,[*] the new plants selected as optimums were the Separately Fired Economizer (Case 3) and the Separately Fired Fossil Fuel Superheater (Case 10). In each case the metal temperature does not exceed 950°F. In addition, provision has been made for potential fouling by providing bare tube surface throughout, widely spaced convection tube banks, and ample soot blowers.

This criterion is perhaps most critical in considering existing steam generators that might be considered for combined refuse-coal firing. The only limitation for modifying existing units for firing refuse on a grate is the grate dimensions, and in most cases the

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[*] See Section III, C.

TABLE II-10

MAXIMUM REFUSE QUANTITY FOR 0.4% ALKALI CONTENT IN MIXED FUEL

		Refuse, St. Louis, Mo.						Coal, St. Louis, Mo.	
		First Sample 4/16/69 Composite		Second Sample 4/29/69 Composite		Third Sample 5/9/69 Composite		Meramec & Labadic 1969 Washed	
		As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Alkalies (as Na_2O)	%	1.43	1.96	0.58	0.76	1.79	2.60	0.18	0.20
Maximum allowable refuse on weight basis	%	13.7	11.4	38.2	35.6	10.6	8.3	-	-
Maximum allowable refuse on heat input basis	%	5.7		23.0		4.15		-	-

		Refuse, Munich						Coal, Munich	
		Ash No. 6 9/8/60		Ash No. 14 1/5/61		Ash No. 18 2/1/61		North, Unit I TÜV Report	
		As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry	As Rec'd	Dry
Alkalies (as Na_2O)	%	1.44	2.46	2.83	4.46	1.80	2.35	0.16	0.17
Maximum allowable refuse on weight basis	%	15.2	10.0	7.7	5.4	12.7	10.5	-	-
Maximum allowable refuse on heat input basis	%	3.7		1.7		3.0		-	-

maximum allowable refuse rate considerably exceeds 10% (heat input), as it should in consideration of economic factors. However, many of the units selected for modification have final steam temperatures near 1000°F. In more modern and larger capacity units, with high superheat and reheat temperatures, in which refuse might be burned either in suspension or on a grate, it would appear that careful attention should be given to problems that might arise from the alkali content of the fuel system.

Coal/refuse ash melting temperatures were of concern even 40 years ago, for the reason that the practice of burning refuse in apartment-house coal-fired heating units was causing ash slagging and high grate maintenance costs. In Reference 51, fusion temperatures of 6 refuse ash samples, 12 coal ash samples, and 26 mixtures of 90% coal ash/10% refuse ash are reported.

In all cases the fusion temperatures of the mixtures were below those of the coal ash samples; in only 15 out of the 26 were they also below those of the refuse ash samples, and these cases included mostly the higher-melting refuse ash samples. The coal ash fusion temperatures range from 1946°F for a Western bituminous coal to 3000°F for an eastern bituminous coal, but a given boiler would be burning coal with a limited range of ash fusion temperatures, depending on the design. However, the refuse ash melting temperatures ranged from 2023 to 2862°F, typical of the range that might be received in a single day at a given incinerator. Thus the conclusion is reinforced that new combined firing plants must be designed to accommodate a potentially large amount of ash fouling; plants selected for retrofit must particularly take the same possibility into account.

There is, however, a suggestion in the data that wide variations in refuse ash fusion points will not carry through to similar wide variations in refuse-coal ash mixtures. The data from Reference 51 are shown in Table II-11, on a grid of increasing individual ash fusion temperatures; those of the 90/10 coal-refuse mixtures are indicated in the matrix, with values lower than those for either component underlined. It is seen that the range is strikingly compressed and that for a refuse ash range of 840°F the range of the mixtures is not more than 109°F for any given coal ash.

C. POTENTIAL POLLUTANT REDUCTIONS

1. Current Incinerator and Power Plant Emissions

The utilization of mixed municipal refuse as a power plant fuel represents an important solution to a rapidly developing solid waste disposal problem. Firing such a fuel, which is characteristically low in sulfur, could also afford a significant reduction in the quantity of SO_2 that must be controlled. Quantifying this aspect of the concept is therefore of considerable relevance to contemporary and future national interests.

TABLE II-11

FUSION TEMPERATURES OF 90% COAL ASH/10% REFUSE ASH MIXTURES

Coal Ash Sample, °F / Refuse Ash Sample, °F	1946	2130	2185	2405	2525	2539	2567	2567	2678	2691	2946	3000
2023			2185	2375					2334		2341	
2090		2081		2290					2225			
2140			2158	2308					2278		2324	
2480			2193	2341					2270		2450	
2665				2324					2302			
2862	1862			2271	2201	2185	2310	2307	2294	2252		2665

According to Reference 52, 41.6% of the national SO_2 burden for the year 1966 emanated from coal-fired power plants (11,925,000 tons/year SO_2). Data from the same source (for 1963) show that the SO_2 produced by coal-fired power plants is equal to about 4.5% of the weight of the coal burned. Reference 53 points out that, for selected urban areas and years in the mid-sixties, coal-fired power plants contributed between 13 and 15% of the total particulate burden experienced in the sampled regions. Unlike the SO_2 emission data, however, the cited level of particulate pollution involves some uncertain level of control.

Using atmospheric burden data for the St. Louis area (Ref. 54) and the above relationships, it can be estimated that for each ton of coal fired to generate electricity, approximately 90 lbs SO_2 and 10 lbs of particulates are released to the atmosphere. In the absence of control, however, the particulate emission rate, according to Reference 44, would be about 112 lb/ton of coal fired. This suggests that power plants in the St. Louis area were, at the time the data was developed, controlled to an extent of slightly less than 90%.

One can compare the above rate estimates with the values recently published by Niessen (Reference 13) on refuse incinerators. Based on a cross-section of typical plants, the SO_2 release rate (without SO_2 APC-equipment) was found to average 2.3 lb/ton of refuse incinerated. The median value for particulates (also without APC equipment) for plants processing more than 50 tpd was 24 lb/ton of refuse processed. Reference 31 indicates that the average particulate emission from incinerators is 17 lb/ton of refuse fired.

The power plant and refuse incinerator SO_2 emission rates invite direct comparison. In view of even current SO_2 APC-practice, the quantities released per ton should have been essentially predicated on the nature of the fuel and its combustion products. Thus one could predict that coal would emit about 40 times the amount of SO_2 produced by the same weight of refuse, or about 13 times that, if one compares the fuels on an energy content basis. In the case of uncontrolled particulates, one would predict that coal would emit 4 to 5 times the amount of dust produced by the same weight of fired refuse. On an equivalent energy basis, suspension-fired coal would produce 1 1/3 to 1 2/3 times the amount of fly ash generated by refuse fired on grates.

In order to determine near - and long-range goals in air pollution control planning, the leading air pollution control officials of each of the LMA's selected for study in this program were interviewed. Annual maximum suspended particulate goals for the LMA's range from 80 to 120 micrograms per cubic meter. Current atmospheric concentrations are on the order of 170 to 200 micrograms per cubic meter. In some areas the target figure of 80 micrograms per cubic meter may not be attainable with the present level of technology.

Target concentrations for sulfur dioxide have been set for several of the LMA's. All represent a substantial reduction when compared with recorded concentrations in the past. Goals for New York City and for New Haven, Connecticut, are 0.10 ppm. The 1974-1975 goal for Philadelphia has been set at 0.03 ppm.

The sulfur content of fuels has been limited in a number of LMA's. The maximum allowable fuel sulfur content in New York City was 2.2% in 1966 and will be reduced to 1% by 1971. In Washington, D. C., the allowable sulfur content has been reduced from 2.25% to 1.5%, and had been scheduled to undergo further reduction to 1% in 1970.

2. Projected Reductions Through Use of Refuse as a Fuel

The impact the use of refuse now available to centralized power plants would have in supplanting fossil fuel is of course an important consideration. Reduced to simplest terms, complete utilization of this commodity with even only a small displacement of fossil fuel energy would still be a welcome solution, now or eventually, to the solid waste disposal problem. On the other hand, complete displacement of coal by refuse would represent a major benefit to APC interests, assuming of course power generation by refuse alone were technically feasible and sufficient quantities of refuse were available.

The total fossil fuel displacement (F) in terms of coal equivalent ($F = W_C + W_{CE}$) becomes, in close approximation:

$$F = P(W_{TMAF}\bar{h}_{MAF} - W_M h_V)\frac{1}{h_C} \qquad \text{(II-5)}$$

where

P = Population

W_{TMAF} = Total refuse collected (MAF*), lb/cap.-day

$\bar{h}_{MAF}$ = Heating value of refuse (MAF), Btu/lb

W_M = Moisture content of refuse**, lb/cap.-day

h_V = Energy required to heat and vaporize moisture, Btu/lb

h_C = Heating value of coal, Btu/lb

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*Moisture and ash free.

**Computed from moisture fractions and percentages of the constituents.

W_C = Weight of coal displaced, lb/day

W_{CE} = Coal equivalent (CE) of weight of oil (W_O) displaced ($W_O \cdot \frac{h_c}{h_O}$), lb/day, where h_O is the heating value of oil, Btu/lb.

The term, F, was determined for the period from 1965 to 2000 for each LMA and for the USA as a whole, based on the calculated value of $\bar{h}_{MAF}$, and on setting h_v = 1120 Btu/lb and h = 12,022 Btu/lb* The results are shown in Table II-12, where for conveience the units have been changed to tons/year.

Figure II-6, based on Reference 55, shows the consumption of various sources of raw energy for the conversion to electrical energy in the U.S. through the year 2000. A curve showing the estimated total number of Btu's available from collected refuse (based on Table II-12) has been superimposed on this figure. It is obvious that a significant amount of coal can be saved by firing refuse in utility-grade boilers. As shown in the table below, the replacement rate will increase with time. This is because the fuel value and the per capita production of refuse are expected to increase at a faster combined rate than will the per capita demand for fossil-fuel generated electricity.

PROJECTED POWER-PLANT COAL DISPLACEMENT BY URBAN REFUSE ENERGY

Year	Available Refuse Energy 10^{15} Btu/yr	Coal Energy Required, 10^{15} Btu/yr	Potential Coal Replacement %
1965	1.6	6.0	26.7
1970	1.8	7.2	25.0
1975	2.1	8.5	24.7
1980	2.5	9.8	25.5
1985	3.0	11.1	27.0
1990	3.5	12.2	28.7
1995	4.7	13.8	34.1
2000	5.8	15.1	38.4

When considered on a national basis, these coal displacement data are only pertinent in a relative sense. Because little coal is used in power plants west of the Rockies, the urban refuse generated in that and other areas of the country could have of course no coal displacement effect.

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*This value is discussed in Section III, B.

TABLE II-12

PROJECTED FOSSIL FUEL DISPLACEMENT BY URBAN REFUSE ENERGY

Year	Urban Refuse Fuel Value, Btu/lb (MAF)	(F) Fossil Fuel (Coal Equivalent) that Can Be Replaced, 10^6 tons/yr						
		U.S.A.	New York	Chicago	New Haven	Philadelphia	St. Louis	Washington DC
1965	9386	67.1	3.9	2.4	0.2	1.6	0.8	0.8
1970	9402	75.8	4.4	2.8	0.2	1.9	0.9	1.0
1975	9416	88.5	5.1	3.5	0.3	2.2	1.1	1.3
1980	9446	104.0	5.7	4.1	0.3	2.7	1.3	1.5
1985	9496	123.2	6.7	4.8	0.4	3.3	1.6	1.9
1990	9570	146.8	7.7	5.9	0.4	3.8	1.9	2.3
1995	9673	192.7	8.3	8.5	0.5	4.8	2.5	3.0
2000	9811	240.3	10.9	11.1	0.5	5.8	3.0	3.7

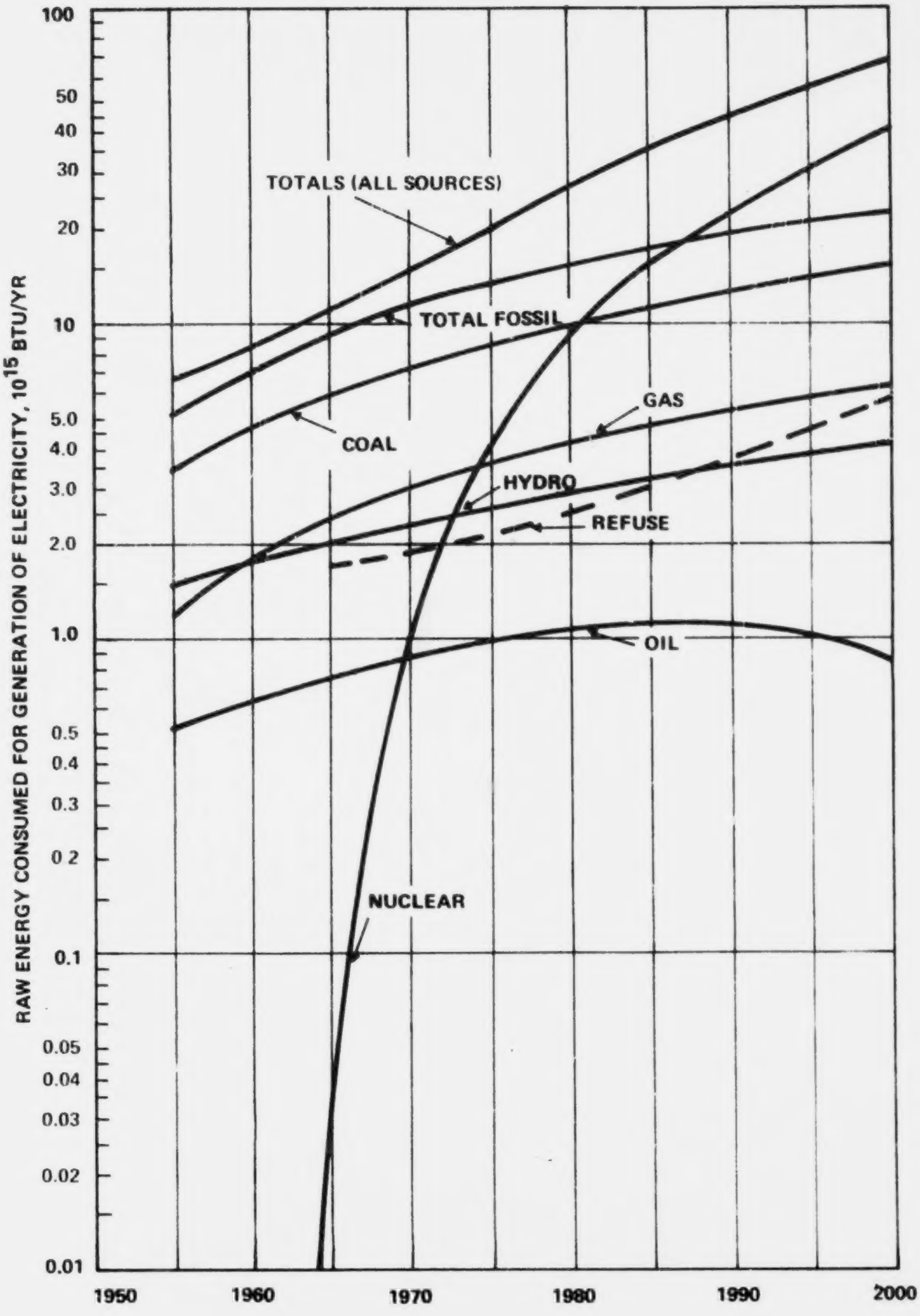

FIGURE II-6. RAW ENERGY CONSUMPTION FOR THE GENERATION OF ELECTRICITY IN THE UNITED STATES

3. Effect of Refuse Firing on SO_2 and Particulate Emissions

In further estimating the potential reductions in pollutant emissions that would result from refuse-firing, certain conditions have been posed. Initially, it was assumed that no SO_2-control is being practiced by electrical utility plants and that particulates would either be controlled at a 95% efficiency or not at all. These conditions were then applied to the situations where the electrical power industry would be supplanting coal with an insignificant amount of refuse or, on the other hand, firing all the mixed municipal refuse that was available.

The nationwide change in SO_2 emissions, ΔSO_2, in lb/day, can be calculated by the following expression:

$$\Delta SO_2 = PW_T S_W - 38.0\ S_C W_C - 39.2\ S_O W_O/2000 \qquad \text{(II-6)}$$

where

S_C = coal sulfur content, wt-%

S_O = fuel-oil sulfur content, wt-%

S_W = fraction of SO_2 generated from refuse, lb/ton

The other terms have been explained previously. The factors associated with S_C (38.0) and S_O (39.2) were obtained from References 44 and 56, respectively. They were originally derived on the basis of assuming that 95% of the coal sulfur and 98% of the fuel-oil sulfur would be emitted as SO_2. The numerical factors thus convert the percent fuel sulfur to equivalent amounts of SO_2 in the flue gas (lbs/ton of fuel fired).

The nationwide change in the dust burden, ΔD, in lb/day, can be calculated as follows:

$$\Delta D = \left(P\ W_T D_W - 16.0\ A_C W_C\right)/2000 \qquad \text{(II-7)}$$

where

W_T = total refuse collected, lb/cap.-day

D_W = particulates emitted from refuse, lb/ton

A_C = ash content of coal, wt-%

One of the operations of the factor, 16.0, used in Equation II-7 is to provide for the release of 80% of the coal ash as stack emission. This rate is based on information contained in Reference 44.

By using Equations II-6 and -7, and the values of F from Table II-12, the reductions in SO_2 and particulate matter were calculated from each LMA and for the nation for the year 1970. The results are tabulated in the table below. The calculation was restricted to a displacement of coal only. Thus the term in Equation II-6 used to express the reduction in SO_2 from oil by the partial displacement of oil with refuse was set at zero. The comparison is for the situation in which substantially no refuse is incinerated, and that in which substantially all refuse generated is used to replace fossil fuels in power generation. Particulate reductions are shown for two cases. In one, no emission control is assumed (described by Equation II-7), while in the other it is assumed that 95%* of the particulates have been removed by APC equipment whether refuse is fired or not; i. e., 5% of the value calculated by Equation II-7 is emitted. The factors used to make the calculations were S_W = 2 lb/ton; D_W = 17 lb/ton; S_C = 2%; and A_C = 7%. S_W and D_W were derived from Reference 31, and S_C and A_C were obtained from Reference 57.

POTENTIAL REDUCTIONS IN CURRENT SO_2 AND PARTICULATE EMISSIONS

Area	Reduction in SO_2, tons/year*	Reduction in Particulates, tons/year Without Control	95% Control
New York, N. Y.	155,000	139,000	6,900
Chicago, Ill.	98,400	87,500	4,400
New Haven, Conn.	7,100	6,500	300
Philadelphia, Pa.	66,700	59,300	3,000
St. Louis, Mo./Ill.	31,400	28,000	1,400
Washington, D. C.	34,700	31,200	1,500
USA	2,670,000	2,400,000	120,000

*Assuming no SO_2 control.

The factor, D_W, is based on a grate-type firing chamber; if suspension type firing were involved, this factor would doubtless increase substantially.

In forecasting the SO_2- and particulate-abatement that would be potentially available in the future, a different set of conditions than those observed for the preceding table were used. Whether refuse is used or not in firing power boilers, the use of SO_2-APC equipment will be indispensable in the overall abatement program. For this reason, the projections for the 6 LMA's shown in Table II-13 were based on the assumption that a 95%

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*The EPA indicated that specification of a control level of 99% would have been much preferred for this analysis.

TABLE II-13

PROJECTED EMISSIONS REDUCTION BY COAL DISPLACEMENT WITH REFUSE
(tons per year)

Year	New York		Chicago		New Haven		Philadelphia		St. Louis		Washington, DC	
	SO_2	Part.	SO_2	Part.	SO_2	Part.	SO_2	Part.	SO_2	Part.	SO_2	Part.
1970	7,000	10,300	4,400	6,500	300	500	3,000	4,400	1,500	2,100	1,500	2,300
1975	8,100	12,000	5,400	7,900	400	600	3,600	5,300	1,800	2,600	1,900	2,800
1980	9,500	14,100	6,500	9,600	500	700	4,400	6,500	2,200	3,200	2,500	3,600
1985	11,100	16,400	7,900	11,700	600	800	5,300	7,800	2,700	3,900	3,100	4,600
1990	13,100	19,400	9,700	14,400	700	1,000	6,500	9,500	3,300	4,800	3,900	5,800
1995	15,600	23,000	12,000	17,700	800	1,200	7,900	11,700	4,100	6,000	5,000	7,400
2000	18,700	27,500	15,000	22,200	1,000	1,500	9,900	14,500	5,100	7,600	6,500	9,600

Note: Above data based on assumption that both SO_2 and particulates are controlled at a 95% efficiency and that all refuse substituted for coal would otherwise be incinerated with the same APC conditions observed.

APC efficiency would exist for both SO_2 and particulates. It was further assumed that all the refuse substituted for coal would otherwise have been incinerated, again with 95% control of the two pollutants. This assumption was considered to be more realistic than to expect that no refuse will be disposed of in incinerators, even though large quantities today do go to landfill sites. In the future, the firing of refuse in power boilers or refractory incinerators will probably become an unavoidable economic necessity.

Reference 54 indicates that SO_2 and particulate emissions from all sources (excluding refuse disposal) are 450,000 and 131,000 tons/year, respectively, in the St. Louis area. On comparing this particular LMA data with that in the table above, it can be estimated that, by substituting all available solid waste for coal, a reduction in SO_2 emissions of 7% can be achieved by combined firing. Similarly, if no particulate emission control were practiced, these emissions would be reduced by 21%, but only by 1% if particulate emissions from power plants (but not other sources) were controlled with APC equipment that furnished a 95% efficiency.

An aspect that should be considered is the fact that of the SO_2 sources extant, the power boiler will probably be the easiest to equip with APC systems and bring under control. If all power plant SO_2-emissions were controlled with a 95% efficiency while all other sources remained unchanged, refuse firing would have a negligible effect on the (now reduced) total SO_2 burden. This can be seen from the following table, which again utilizes data for the St. Louis area.

EFFECT OF COAL DISPLACEMENT BY REFUSE ON SO_2 EMISSIONS FROM ALL SOURCES (ST. LOUIS AREA)

Total SO_2 Controlled, %*	SO_2 Reduction by Refuse, %
100	6.7
80	1.4
60	0.8
40**	0.5

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*Assuming 95% control efficiency and all power plants controlled.

**Approximate point at which all power plants but no other SO_2 sources would be controlled.

In the present discussion, the possible reduction of NO_x emissions has not been considered. This aspect of the analysis, which actually is somewhat outside the scope of this study, is difficult to quantify. The level of NO_x emissions will vary with combustion conditions. Furthermore, the control efficiency that can be assumed is problematic in the absence of a practical NO_x-APC methodology and the relevant process information. One can, however, acquire a qualitative appreciation for the potential NO_x reductions that would be implicit in refuse substitution by comparing the data on NO_x emissions from refuse incinerators and coal-fired power plants. Such data have been presented in Section IIB, 2, b(1).

D. HANDLING AND PROCESSING

1. Introduction

European practices in the physical handling of refuse prior to and after combustion could be considered advanced compared to those in the U.S., but the degree of superiority is really a small one and could more accurately be described as "experienced" rather than one involving application of sophisticated technology.

Refuse, once collected, may be classified (sorted, with or without recovery of salvage values), altered in size, mixed, transported, stored, dried, introduced into a combustion chamber, and, after varying degrees of burn-out, the residue (or products, in the case of pyrolysis) collected for subsequent use or disposal. Each of these processes is practiced to some extent in conjunction with the steam raising - refuse furnaces constructed in recent years. The design of much of the equipment employed is directly transferred or adapted from other fields, and consequently oftentimes is of lower efficiency or higher cost than would be the case if optimized specifically for processing refuse. Increasing attention being given to the solid waste problem by both government and industry has stimulated development of potentially superior equipment and integrated systems in the last several years. Unfortunately, the results of most of this work are just becoming available and little can yet be said about cost effectiveness, particularly that relating to maintenance. In a number of cases, the process itself is considered proprietary and design information is not available. Several new industrial and municipal incinerators are about to become operational and the knowledge to be gained from a year's operation of these facilities will be far more meaningful than performance estimates now based on rather large extrapolations or on conclusions drawn from only remotely similar systems.

In each of the processing steps cited above, it is apparent that rather large improvements should be realizable over current practices. The necessary developments will probably not be made nor the cost benefits enjoyed unless a significant number of sizeable plants are built. That size reduction can add \$1 to \$3 per ton to refuse burning is not sufficient incentive in itself to cause grinder or hammermill manufacturers to develop equipment designed specifically for the handling of refuse at energy consumption and wear rates approaching theoretical. In spite of glass cullet having a value of \$20/ton and scrap aluminum being worth \$200/ton, there are no techniques yet in full scale operation for efficiently separating away such materials once they have entered the normal mixed waste collection system. The need is now being recognized for totally improved solid waste disposal schemes, including recycle and salvage concepts, and once a market is established, innovations in processing equipment will soon be forthcoming. In the meantime, the municipality or utility desiring to construct an energy recovery refuse incinerator can rely on U.S. consulting engineering firms to recommend well-tried and readily designed types of equipment available at the time of bid solicitation.

Little summary information is available on refuse processing equipment. Battelle Memorial Institute assembled much pertinent data that apparently never received general distribution, although its principal conclusions regarding grinding costs have been reported elsewhere (Ref. 58 and 59), and a modified edition has been recently released (Ref. 60). A large portion of the information in this field consists of manufacturers' literature or rather qualitative descriptive articles of the use of commercial equipment, oftentimes under conditions having only remote resemblance to the desired application to refuse treatment. Wide variations in performance and cost claims are to be noted to the point where a compilation of such information serves little purpose. Rather than attempting any exhaustive listing here, in the sections that follow are presented the critical facts concerning those refuse processing steps that would have applicability at some stage in an energy recovery system. Because refuse size reduction is an indispensable unit process where suspension fired steam generators are concerned, this topic was given particular attention. In this connection, samples of shredded refuse were analyzed for size distribution to permit the estimation of the burning characteristics of such material in suspension fired furnaces.

2. Size Reduction

a. Equipment Characteristics

In the several compilations of descriptive information on size reduction (Refs. 58, 61, 62), much of the data is concerned with devices of limited application to mixed refuse grinding at high throughputs. Brittle materials are ideally broken up by one type of equipment, tough materials by another, fibrous ones by still a third, etc. When the several physical types are combined, as is the case with municipal refuse, a compromise design must be employed. Typically, this has taken the form of some variation of a hammermill, with the striking-bar configuration and the orientation of the axis and the direction of rotation being the principal differences offered by the fifteen or so U.S. and European manufacturers.

Single mills have been built that could handle as much as 50 to 75 tons/hr of refuse, requiring some 10 horsepower/ton-hr in this range to drive them. Essentially all of the still relatively few mills actually being used for refuse grinding in Europe or the U.S. are considerably smaller than this (10 to 20 ton/hr).

In the Battelle study mentioned above, it was noted that the nature of the feed material and the size of the milled product are important parameters in determining the amount of drive power that needs be applied. It was pointed out, for example, that sorted municipal solid waste required only 65% of the power that must be used to mill unsorted refuse. It was not clear, however, which ingredients would be removed in the sorting process. The increase in power required to achieve smaller product top sizes in a single pass was given as follows:

Top Size, in.	Horsepower per ton factor
6	1.00
4	1.39
2	1.64
1	2.38

As shown in Reference 13, which reviews these same data, the relationship of comparative power use to product top size is a linear function, with which the power factor for the 2 in. top size is in poor agreement. The author suggests therefore that the value is in error and should be 2.00 rather than 1.64. The significant reduction in throughput that results from the production of small top size material is usually avoided by using several stages of milling.

Cost information, be it capital, operating, or maintenance, is still difficult to assess because of (1) differences in design features and accessory handling equipment; (2) the lack of an efficiently operated, long term, size reduction project; and (3) physical differences of input refuse (composition and size) and ground material (size) from one user to the next. After adjustment for escalation, the recent sales price of $125,000 for a 70 ton/hr grinder appears to well fit the curve offered in Reference 13 for a variety of equipment capital costs; other costs on this averaged curve include $80,000 for a 50 ton/hr unit and $35,000 for a 15 ton/hr unit. A 6-in. top size product is typically assumed for deriving the throughput rates in such cost figures. Experience by several of the large equipment manufacturers and at operating demonstration facilities such as Madison, Wisconsin (Ref. 63), indicate maintenance costs (primarily re-facing of the hammers) to be on the order of $0.20 – 0.40/ton and electrical costs of $0.10 – 0.15/ ton of refuse.

In Reference 13, the Battelle data were further analyzed to develop total capital costs for shredding mixed municipal refuse input for incinerator plants sized from 120 to 1200 tpd. Cost data were presented for 6, 2, and 0.5 in. top size output material. It was shown that total shredding costs for any given product top size decreased significantly as plant size increased within the smaller capacity range but that little economy of scale resulted when plant sizes exceeded about 900 tpd.

Relying on the costing method developed in Reference 13, grinding costs for a set of product top sizes that would be more appropriate to the present study were calculated. The only deviation introduced was in the assigned equipment life expectancy (10 yrs vs 15 yrs) and, thus, in the rate of annualization of capital costs (14.6% vs 9.7%). The results obtained are shown below:

SIZE REDUCTION - TOTAL CAPITAL AND OPERATING COSTS
(Costing date basis: July 1969)

Nominal Top Size of Product, in.	Shredding Cost, $/ton of Input
6	1.20
4	1.62
2	2.20
1	2.57

These costs are based on a plant refuse rate of 1200 tpd operating 2 mills 1 shift per day and 5 days per week. As pointed out above, these costs would probably change but little for other refuse rates in this general range.

b. Test Work

Because of the potential importance of refuse reduction operations in improving the burning process, some effort was devoted to characterizing the output from representative grinding machinery. This was done (May 1970) on refuse being routinely prepared for landfill at Madison, Wisconsin, by a 200 HP Tollemache hammermill and that ground during a demonstration at Albuquerque, New Mexico, by a 700 HP Eidal mill. In both cases, the feed material was sampled and sorted into constituent classifications to establish composition. These analyses indicated, as shown in Table II-14, that the Albuquerque refuse was unusually low in garden refuse and that the Madison refuse was rather low in paper content. This is explicable in that Albuquerque is not heavily vegetated even in May, and in Madison waste newspaper was being collected separately at that time for recycle purposes. The particle-size distributions of the materials output by the mills are shown in Table II-15.

While both mills produced a significant amount of material that was well in excess of the arbitrary 1.5-in. maximum sieve size observed in the analyses, the amount of very small particles was impressive. Regardless of the nominal top-size of the product, both mills furnished considerable material which should burn rapidly in suspension-fired furnaces.

TABLE II-14

REFUSE COMPOSITION OF HAMMERMILL INPUT AT TWO AREAS SAMPLED

Component	Weight - Percent	
	Albuquerque	Madison
Garbage	9.3	13.3
Garden Waste	1.6	9.1
Paper Products	42.1	28.4
Plastics, Rubber, and Leather	7.1	10.9
Textiles	7.9	5.6
Wood	1.5	1.4
Metals	17.2	15.3
Glass and Ceramics	11.6	14.9
Ash, Rocks, and Dirt	1.7	1.1

TABLE II-15

PARTICLE SIZE DISTRIBUTIONS OF OUTPUTS FROM TWO DIFFERENT TYPES OF HAMMERMILLS

Fraction and Predominant Constituent	Nominal Top-size		
	Albuquerque	Madison	
	4-in.	6-in.	4-in.*
Plastic film, paper, cardboard, > 1.5-in.	5.1	31.9	6.9
Wood, > 1.5-in.	4.3	3.8	0.5
Metal and Rocks, > 1.5-in.	8.8	19.6	0.5
Mixed Material, < 1.5-in.; > 0.25-in.	22.2	20.5	27.3
Mixed Material, < 0.25-in.	59.6	24.2	64.8
Sample Wt. Loss between Sampling and Analysis	12.8	10.8	3.3

*Additional hammers were installed in the mill to produce the finer grind.

The sample dehydration losses noted were unavoidable. They reflect the time elapsed between collection and analysis, the time spent in performing the analyses, and the receipt-condition of the plastic containers in which the ground refuse was shipped from the sampling sites.

A further test on these grinder products was performed to establish the feasibility of effecting, for firing purposes, a separation of the various size-fractions produced. The device tested, the Zig-Zag Separator (see Section II, D, 4, d), was generously made available by the Stanford Research Institute at Irvine, California. A quantity of the finer-grind output from the Madison hammermill was processed through a separator having a 6-in. wide classification duct. When operated at a pressure drop of 6.5-in. W.C. (vertical air velocity = 21-25 ft/sec.), 79.2% of the material elutriated. Although this fraction contained some large pieces of thin-film, plastic and paper pieces, it was an excellent mixture for firing in suspension. The other fraction, 16.8% of the total, contained a bulk of the oversized, non-film pieces and denser non-flammable material. It represented an excellent concentrate for salvage processes and a subsequent second pass through the grinder. About 4% of the sample could not be accounted for. This was lost through evaporation and in dust fines.

c. Effect of Particle Size on Combustion

The immense success of pulverized coal combustion in large utility boilers has caused interest to be given in recent years to improved incinerator designs where some form of suspension burning would be approached. A large furnace for ground industrial waste and sewage sludge has been undergoing testing in Rochester, with as yet undisclosed results, and modifications are in progress in St. Louis to fire ground municipal waste in combination with coal.

While much has been written on combustion theory of carbon particles (Refs. 64 and 65, for example) and even refuse particles (Ref. 66), application of this work to mixed refuse is difficult because of the nature of the physical surface of the latter. Taking, for example, the hammermill product characteristics shown in Table II-15, one can calculate burning times for the various fractions. Using the pyrolysis and combustion equations presented in Reference 66 and assuming that mass transfer controls the rate of burning, the data shown in Table II-16 was derived for the 4-in. top size material sampled at Madison, Wisconsin.

If the theory on which the calculations were based is correct and the particles are adequately represented by the shapes and average dimensions specified, an obvious problem exists. Suspension firing of the material described in Table II-16 would be accompanied by much fall-out and elutriation of incompletely burned material. Neglecting the wood fraction, which is not in high enough concentration to be of concern, the slow burning

TABLE II-16

CALCULATED BURNING TIMES FOR VARIOUS FRACTIONS IN MILLED REFUSE
(4-in. Nominal Top Size)

Fraction and Predominant Constituent	Fraction of Total, wt-%	Assumed Average Particle Dimensions				Total Time for Pyrolysis and Burning, sec.
		Shape	Length, in.	Thickness, in.	Dia., in.	
Plastic Film, Paper, Cardboard >1.5-in.	6.9	Slab	4	0.01	-	15
Wood, >1.5-in.	0.5	Slab	2	0.2	-	600
Metal and Rocks, >1.5-in.	0.5	-	-	-	-	-
Mixed Material, <1.5-in; >0.25 in.	27.3	Sphere	-	-	0.8	950
Mixed Material, <0.25-in.	64.8	Sphere	-	-	0.1	20

Assumed Combustion Conditions:

Gas temperature = 2370°F; Relative velocity between particles and ambient gas = 10 fps.

particles would arise essentially from the large (27.3%) fraction of mixed material in the 0.25 to 1.50-in. diameter range.

With the exception of the inert fraction (>1.5 in.), this fraction was observed to be the least uniform of the cuts. Characterizing it as a granular mixture of spherical particles would be highly inaccurate. In addition to some inert pieces, composite artifact fragments, splintered wood, and various other irregularly shaped items, it contained considerable quantities of paper and cardboard, occluded with foreign matter, that ranged from loosely crumpled to compressed structures containing both crushed, convoluted film bodies and much coarsely filamentated material.

Such bodies would not likely burn as would truly spherical particles during dehydration, pyrolysis, ignition, and combustion in a hot gas. The uncompressed pieces would probably behave as thin slabs and be burned out in 10 to 15 seconds. The clumped structures, on immersion in the hot gas, would likely undergo several processes. Filaments and protruding film flaps would burn off quickly while the main body dehydrated and pyrolyzed. The latter effects, however, would release considerable quantities of gases within the body and cause rupture and displacement of the intersticial folds. This would cause the agglomerated structure to open up, expanding the body considerably and presenting new film surfaces. Thus the burning process should be much more rapid than for a sphere of cellular or finely consolidated composition. It would be very difficult to estimate the burning time of such material on the basis of combustion modelling. Because several full-scale, suspension-fired systems are or soon will be under test evaluation, this question should soon be answered.

3. Refuse Transport

a. Background

The transportation of refuse is defined as the process of moving the collected material from the area of production to the disposal site. In landfill disposal operations, it would include the travel of the packer truck, once it has been filled or completed a collection route, to the site and, for cost purposes, the return of the empty truck to the route. If transfer stations are employed, transportation would include the movement of both the packer trucks to the station and the transfer trailers, barges, or railroad cars to the disposal site, and, for cost purposes, the return of the empty carriers to the collection routes and to the transfer stations, respectively, and the cost of operating the latter.

Other intermediate processes interrupting the transportation process can be considered. At Madison, Wisconsin, for example, packer trucks deliver refuse to a shredder plant, the output from which is compacted into trailers for outhaul to an adjacent landfill. Here of course the shredding operation would be considered to be a unit process and not part of the transportation operation.

losses. A cost analysis made by Zandi demonstrates that with the present state of the art, pipelines become competitive with truck hauling when the distance to the disposal site is 50 miles or more. With only moderate improvements in system components, pipelines should become equal in cost to vehicles at approximately 25 mile haul distance.

With the above research demonstrating that water slurries of waste are readily pumped, consideration should be given to the use of fuel oil as a carrier. Such a system would not only eliminate the need for drying of the refuse prior to combustion, but would minimize many of the on-site handling problems now causing utilities to shy away from using wastes as a fuel.

4. Separation Processes

a. Background

An indication of the present inferior state-of-the-art of refuse sorting techniques is the emphasis now being made to encourage and support new developments in this field. While recycle and salvage are of principal concern from an economic and social (resource utilization) viewpoint, the sorting of mixed municipal refuse would also affect the design and costs of heat recovery incineration systems. Heating values would be increased or decreased depending on the recovery practices employed for paper, plastic, and metal fractions; grinding and handling procedures would be based on the new physical characteristics of the modified refuse*; superior combustion methods could be utilized and fireside corrosion minimized; and final residue disposal would be simplified.

Magnetic separation of iron from refuse has been practiced for a number of years. In the case of incineration, removal of this fraction typically is accomplished after burn-out and water quench. Hand sorting from a conveyor belt has been utilized where low cost labor is available, primarily in conjunction with composting operations. Automatic separation into a number of fractions at sufficiently low cost to obtain salvage credits has not yet been commercially demonstrated. Research is in progress at the Bureau of Mines (College Park Metallurgy Research Center, Salt Lake City Metallurgy Center, and Tuscaloosa Metallurgy Research Laboratory), a number of universities and research institutes (West Virginia, Missouri, Stanford, M.I.T., Alabama, Wisconsin, MRI, and SRI, for example), and several industrial organizations, where the results are considered quite proprietary. The basic techniques being studied have been treated by the authors at Battelle (Ref. 60), SRI (Ref. 71), MIT (Ref. 72), and MRI (Ref. 73).

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*Assurance that all hard objects had been removed, for example, would permit selection of pulverizers having far lower capital, operating, and maintenance costs than present equipment.

Automatic sorting processes rely on two chief principles: (1) subdivision of material into pieces having a more or less homogeneous composition, sensing of the uniqueness of each piece by means of one or more devices capable of measurement of properties (density, electrical, optical, hardness, etc.), and diversion of the classified piece to specific hoppers; and (2) utilization of properties themselves to cause classification, as with magnetic attraction or repulsion, floatation within a liquid or gaseous stream, or screening to remove finely crushed components such as glass. While capital and operating cost reductions are most essential to the successful incorporation of classifiers, other problems that remain include the difficulty in arriving at a homogeneous material (the aluminum steel-lidded can, etc.), and the development of products best suited to utilize salvaged materials.

b. Ferrous Metals

The tin content of ferrous residues from municipal incinerators runs between 0. 1 and 0. 4% (Ref. 74). This contaminant level makes this form of scrap unattractive to iron processors for whom an ample supply of more desirable scrap is already available in most areas (Ref. 73). The principal use for ferrous metals recovered from refuse is in the precipitation of copper from acid leachates of lean ores. In the required form, the metal brings \$50 to \$60/ton in this market, the highest price paid for steel scrap in this country. Precipitation iron must, however, furnish a high surface area with a minimum of further processing at the mine works. This requires that the salvaged material be shredded and loosely packed (20-25 lb/cu ft) when shipped. Because the main use points are in Arizona, Utah, Montana, and Nevada, an obvious limiting factor is transportation cost.

The prospects in this market for ferrous metal salvaged from refuse are not encouraging. Copper refiners are slowly moving away from refuse scrap iron to better grade materials. Many are shifting over to detinned scrap originating from tin plate producers. The reason for this is that ferrous metal, after separation from refuse and customary processing, does not perform well in the copper precipitation process because of its highly oxidized state and the presence of foreign materials. If the reclamate could be better cleaned and detinned, this situation could be reversed.

Removal of ferromagnetic material from refuse (whole or shredded) is best accomplished after the latter has been fired. The volume of material that must be passed through the sorter is greatly reduced and the salvaged iron is essentially sterile. In certain types of shredded-refuse firing steam generators it may be preferred to remove this fraction from the input material if corrosion is a serious problem.

The most popular method of iron removal involves the use of suspended- and/or pulley-type magnetic separators. The former usually consists of a short conveyor loop, the bottom belt of which runs slightly above and across the feed conveyor. A magnet is situated between the pulleys so that iron in the feed is deposited on the upper conveyor to ride off laterally into a receiver. In the pulley-type magnetic separator, the end pulley on a discharge conveyor is magnetized. As the feed material pours off the end, iron follows the rotating pulley and detaches, when out of the field, in a separate line of fall.

Including costs for power, maintenance, and annualized capital costs of the equipment, which is rather inexpensive, separation cost is minimal (≤ $0.10/ton). Output from the separator can be sold to metal processors for between $13 and $15/ton.

c. Non-Ferrous Metals

Over the last 10 years, Vanderbilt University has been examining the concept of utilizing magnetic force ("eddy currents") for the separation and sorting of conducting, non-magnetic, materials from non-conducting ones, after initial removal of iron fractions by conventional electromagnets. Much progress has been made in the development of practical equipment for this operation at feed rates up to several hundred lb/hr, and a unit for separation of 1200 lb/hr is now being assembled. While most of the work has concentrated on processing shredded cars, limited testing with the non-ferrous fraction of incinerator ash has demonstrated that some 93% of the aluminum metal can be isolated in an essentially pure fraction. In a recent report (Ref. 75) describing the methods being investigated, a cost analysis based on actual performance data was presented indicating that a 25% increase in profits would result in the scrap car business if the Vanderbilt sorter were to be used. The plant was assumed to process 66 tpd of a mixture containing 82% iron; 14% paper, cloth, and plastic film; 2% rubber, dirt, and glass; and 2% non-ferrous metal. This latter fraction was sorted into 6 components (aluminum, copper, zinc, chromed zinc, brass, and stainless steel), with the total cost of grinding all input material and conducting the necessary separations estimated to be $2.25/ton.

d. Air Classification

Air has been used for the size classification of solid particulate matter for a number of years and recently attention has been given to its use for separation of solid waste into fractions. Among the schemes being considered, the so-called "zigzag" classifier being developed by the Stanford Research Institute (Refs. 71 and 76) probably offers the greatest efficiency at low costs. This device consists of a series of ducting sections with a turning angle of 60° at each corner; a throat section of 2 in. x 6 in. was present in most tests, up to 12 stages employed, and blowers capable of creating air velocities up to 3000 fps used. Shredded mixed materials are added part way up the columns and the air flow adjusted to cause a given binary separation, with heavy objects and those with low drag coefficients settling under the influence of gravity. The secondary air flow patterns within a zigzag column, compared to a completely vertical one, permit maximum aerodynamic separation of particles. Work has proceeded at SRI to a point where the behavior of various solid materials in an air stream can be measured and the characteristics of separated fractions predicted. Analysis of a 30 ton/hr facility indicates that approximately $0. 10/ton would be the cost for a given binary separation, exclusive of the required grinding costs.

Such a process could of course be used to beneficiate a steam generator refuse fuel while isolating a fraction high in inert content. The latter might then be advantageously used for the salvage of metals and, possibly, glass. It is also possible that such a device could be installed in-line with part of the primary combustion-air system of a suspension fired furnace. This technique is now being tested in a vertical duct arrangement on the CPU-400 (Ref. 77), an advanced type of pilot system described a few paragraphs below.

E. ENERGY UTILIZATION

1. Turbo-Electric Generation

a. Rankine Cycle Systems

All, or a portion, of the thermodynamically available energy content of steam generated from external combustion of refuse can be converted to electricity through expansion of the high temperature and pressure steam through any of a variety of turbine systems. The refuse can serve as the sole heat source or be used in combination with fossil fuels. Typical design features of conventional boilers are discussed in Appendix B (Volume II).

b. Gas Turbine Systems

Rather than transfer of heat to a working fluid as is accomplished in the Rankine cycle, it is possible to directly use hot combustion gases to impart rotary motion to a gas turbine. Distillate oil-fired gas turbines have become common in the electrical utility industry, particularly for relatively small units for the rapid supplying of peak energy demands.

A number of refuse-fired gas turbine systems have been suggested. The one presently receiving the most attention is that being developed by the Combustion Power Co. , the so-called CPU-400 (Ref. 77). This unit, intended to produce 15 MW of power from the combustion of 400 tpd of solid waste, also yields 250 lb/sec of gas at 950°F that can be used for process heat, sewage sludge drying, desalination, etc. The design incorporates shredding, air classification for the removal of inerts and heavy objects, and partial drying of the refuse using a small amount of the waste heat.

Combustion in the CPU-400 system occurs within a 100 psia reactor, where inert sand particles are fluidized by means of 584°F air from the compressor. Fly ash and fines from the fluidized bed are removed prior to introduction of the 1650°F gas into the turbine by inertial separators and an electrostatic precipitator. Ash that is heavier or larger than the bed sand will be periodically removed from the reactor bottom through a rotary air lock. Each of the critical hardware elements has been tested with sub-scale equipment and further developmental work with larger units is in progress.

Full economic evaluation of this concept cannot be completed until additional engineering tests indicate the degree of complexity of the combustion and gas cleaning equipment, turbine life, etc. Preliminary costs have been estimated by the Combustion Power Co., but direct comparison with values derived on this program should be avoided. The capital cost of $4 million corresponds to $10,000 per ton per day incinerator capacity or about $375 per kw installed capacity as electric plants are evaluated. This compares with $120-140/kw for present stations in the same size range (Ref. 78). Under private company ownership, it is estimated refuse disposal costs would total $5.99/ton, without credit for by-product sales. With credit for electric power (82% load factor and 4.5 mills/kw-hr), disposal costs are estimated at $2.67/ton. Municipal ownership is claimed to lower these values to $4.27 and $0.95/ton. Utilization of the turbine waste heat would further reduce these costs.

2. Other Applications

Heat from the combustion of refuse may be used in numerous ways to benefit the surrounding community. In addition to the obvious use for electrical power generation, there are several other potential end uses that deserve consideration. Among these are industrial and district heating (and cooling), desalination, and various miscellaneous applications. These uses utilize steam of a relatively lower grade than that required for power generation, and in some cases could use the steam discharged from another process. The secondary heat sources that may be considered in this respect are: (1) the steam bled from one or more stages of an extraction turbine, (2) the discharge from a back pressure turbine, (3) output from a low pressure boiler, and (4) steam discharged from some higher level process. The last option may permit the cascading of two or more uses in series.

a. Industrial and District Heating

Heat from refuse could be used by many different industries, ranging from chemical processing plants to food packing to commercial laundries. The form of energy required varies over such a broad range that each particular industry would have to be evaluated on an individual basis. This is not to imply that industrial heat should be disregarded as a potential use for refuse energy, but that the type and density of the surrounding industries may well dictate the steam conditions and steam generating equipment required. District heating has become of increasing importance for space and hot water systems. Tremba (Ref. 79), in his recent review of all known district heating systems, indicates the output magnitude of present installations. During the years 1965-67 some 2.9×10^{15} Btu's were distributed, 88.5% within the Soviet Union* and 9.1% within the western world. In combined heat and power plants, approximately 1.1×10^{14} watt-hours of electricity were produced. Of the 226 heating installations surveyed in the western world, 21 stated they used refuse as a portion of the fuel for the boilers.

In Denmark, 30% of all dwellings are now heated from central boiler plants, and this is expected to increase to 40-45% by 1975 (Ref. 80). About 450 plants have been built, and operation has been successful at dwelling densities as low as 4/acre. Normally, pipe lengths from the boiler to the farthest consumer are less than 2.5 miles. It is estimated that an annual 38 lb SO_2/dwelling connected to the heating system is no longer discharged at the previous low levels of home chimneys. Selling price to the small user in Denmark is in the range of \$0.80 to \$1.60/10^6 Btu, which accounts for the popularity of these heating systems (allowance should be made for the elimination of capital and maintenance costs of individual home furnaces and water heaters in comparing such heating costs). Mørch (Ref. 80) estimates that in Denmark a city's refuse would cover 6 to 8% of the heat consumption over the year, and that if the usual wider refuse area is considered, this percentage would be significantly greater. A test facility has been built for producing gas from refuse (7 ft^3/lb), which, after carburetting with 3.4% butane, has a heating value of 510 Btu/ft^3. Evaluation is now being made for use of the plant waste heat plus the gas manufactured in a district heating plant, as well as supplying a portion of the gas to city mains.

Kimura (Ref. 81) gives emphasis to the need for an industrialized, high population density nation such as Japan to develop a plan for optimum utilization of all energy factors. Within his recommended "circulation network of city energy," the burning of refuse plays an important role in a number of heat generating systems.

In his review of district heating systems in the Mannheim area, Winkens (Ref. 82) described that city's Nord plant in which 80 t/h of refuse is fired in two boilers in addition to three oil-fired boilers. Steam is supplied to transmission grids at both 20 and 7 atm pressure, with some 250,000 tons being supplied in 1969 from the incineration of 130,000 tons of refuse. Expansion of the waste burning facility is planned in the near future.

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*The siting of power facilities within cities has led to low distribution costs of both heat and electricity in Russia, with consequent extensive employment of district heating. In Moscow, for example, 22,000 buildings and 360 industrial plants are connected to a heating system containing 750 miles of pipe.

Britain's first combined refuse incinerator and district heating plant is being constructed in Nottingham (Ref. 83). The output will increase through planned expansions to 440 million Btu/hr by 1980. At this latter time, some 170,000 tons of refuse per year would be burned, providing up to two-thirds of the total heat output (remainder from coal). Steam from separately-fired coal and refuse furnaces will be used for electrical generation and the supplying of hot water at 285°F and 85 psi to distribution mains. Reduction of about one-third in the cost of heating and hot water are anticipated.

The Northwest incinerator plant in Chicago, now under construction, will utilize a portion of its steam for district heating (Ref. 84). An average production of 3 lb steam per lb refuse is anticipated and the facility is designed to handle 560,000 tons per year of refuse. Most feedwater pumps and fans at this plant will be steam turbine driven once start-up is achieved.

The most advantageous applications of absorption refrigeration are in cases where suitable amounts of low-grade heat are available, such as can be the case with a refuse-fired boiler. Where reciprocating compression machines are limited by volumetric displacement, the absorption machines can maintain capacity at lower back pressures by increasing the flow of heat to the generator. Absorption systems generally require no special building considerations. With the application of suitable controls, the absorption system will operate with very little attention. Absorption refrigeration systems have been built in capacities of 2000 tons (24×10^6 Btu/hr). The absorption system does not respond well to rapid changes in load, but should operate nicely in a district cooling application where the load is averaged by the distribution system. Conventional compressor driven refrigeration or heat pump systems could also use steam turbines as the driving device in large district cooling or heating systems.

No detailed analysis has yet been made of the size range over which economical operation of district heating from refuse combustion might be realized. Rather typical of the qualitative analyses that have been made is that of Beningson (Ref. 85), where wide application of incineration energy is encouraged, but not justified on an engineering or economic basis.

A generalized economic optimization of a dual-purpose (heat and electricity), multi-fuel (refuse and fossil), steam generator is affected by a large number of variables, chief among which are:

- Regional electrical demand and anticipated growth rate
- District (local) heat demand and anticipated growth rate
- Distribution of population density (cost of transmission system*)
- Temporal effects on output demand for both services
- Annual outdoor temperature statistics
- Fossil fuel costs (heating basis)
- Refuse haul and processing costs
- Refuse heating value
- Factor costs (capital charges and labor).

These determinants will indicate the basic steam cycle that will lead to lowest annual costs for the total system (refuse disposal, heat supply, and electrical generation), which in turn would permit firm design of the furnace-boiler-turbine-condenser components. At the 1st International District Heating Convention held in London in 1970, a number of suggestions were made (Refs. 82, 86-93) for optimization techniques for dual-purpose plants using fossil fuel only. Adaptations of these could be made for the more complex case with waste fuel for a specific set of assumptions.

b. Desalination and Miscellaneous Applications

Waste heat can serve as an excellent evaporation source for a desalination facility. Plant optimization depends upon factor costs, but a typical yield of fresh water from brackish or sea water is about 10 lb per lb steam (Ref. 94). In areas where natural water shortages exist, the use of the energy from refuse combustion should definitely be considered, particularly after a portion of the energy has been extracted in a turbine system.

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*It is essential that the heat consumers be near the generating facility, while this is not the case for the users of the electrical energy. However, a privately owned dual-purpose plant can still compete with grid power in spite of higher electrical generating costs when their distribution costs are small.

Steam derived from fossil fuels has been used for snow and ice melting on sidewalks, roads, and airport runways: properly designed systems using refuse as a fuel should offer significant cost advantages. Other potential applications include the use of refuse-derived steam as the motive power for driving pumps, fans, and ejectors. Where linear actuation is required, steam has been satisfactorily used for purposes ranging from clamping and punching operations to the catapult launching of aircraft. Acoustic generators of many types are used in industrial applications. Considerable interest has developed in jet cutting of many materials and here steam could supply the required energy for many such operations.

III. POWER PLANT DESIGN CONSIDERATIONS

A. STATE OF THE ART SURVEY OF FOSSIL FUEL AND REFUSE-FIRED BOILERS

1. Fossil Fuel Boilers

The generation of steam from the combustion of a fuel, whether it be a fossil one or a waste material, is simple in concept, yet a highly specialized technology when long-term cost minimization is a requirement. Fortunately for the cause of future heat recovery incinerator systems, the fossil fuel boiler industry in both the U. S. and Europe is dynamic and innovative, and a rather considerable history of continuing efficiency improvements exists. An understanding of the basic art is important to many individuals whose function it is to formulate recommendations or decisions on the purchase of boiler equipment. Such an understanding is not essential, however, to an appreciation of the conclusions presented in Volume I of this report, and development of the detailed background information is therefore reserved for Section III of Appendix B (Volume II).

All trends within the thermal electrical utility industry, other than price of the product, have been those of spectacular growth. In recent years, unit sizes have increased by more than a factor of ten, the quantity of power produced per unit mass of fuel by a factor of two, steam pressures and temperatures have reached levels previously thought impractical, and demand has steadily increased at 7% per year. These accomplishments have been realized through the development of a variety of designs of furnaces, heat exchange systems, and auxiliary equipment, key features of which are described in the referenced appendix section. These fossil fuel plant designs are important to the present analysis of heat recovery combustion of solid waste in an air pollution-free manner for the following reasons:

- Only combined firing (coal/oil and refuse) systems are being considered, with a significant portion of the heat always being obtained from the fossil fuel for reasons of systems control.

- Radiative and convective heat transfer are affected only slightly by fuel composition; the vast experience gained in conventional boilers in steam cycle optimization can be directly applied to dual-fuel plants.

- Coal ash compositions have been sufficiently variable throughout the industry that prediction of corrosion and fouling can be based on elemental analysis; these theories can now be applied to proper design of combined fired systems.

- Cost estimates for refuse combination systems gain increased accuracy when the experience with conventional boilers is used.

- Air pollution control technology now used or being developed for fossil fuel systems is directly applicable to refuse systems.

2. Refuse Installations

Section V of Appendix B (Volume II) describes key features of selected refuse fired steam generators. Reference should be made to the Bibliography (Appendix D) for a listing of general reviews of design characteristics of such refuse burners and discussions of specific configurations of a number of recent units. Plants that can consume several thousand tons per day of refuse have been built and are being operated with no greater problems than those experienced in a comparable size facility using coal only as a fuel. The use of a number of different agitating grate systems and properly designed air introduction schemes permits a high degree of burn-out. The water walls used for steam generation reduce the volume of gas to be handled by the air cleaners while simultaneously permitting lower operating costs through sales of steam to electric utilities or central heat distributors.

B. CATALOG OF CANDIDATE SYSTEMS

1. Introduction

An important task of this program has been the development of engineering and cost data on possible boiler configurations fired by refuse. The catalog of such cnadidates can then be systematically analyzed to identify those design forms which offer the more favorable bases for optimization. The selection of such systems has been based on the state-of-the-art survey, discussed in Appendix B, Volume II, and the characteristics of refuse, discussed in Section II. An aim, in developing this catalog, has been to propose two classes of designs. Category I is intended to include systems that would influence new plant design and construction. Category II systems are applicable to "retrofit" situations, wherein the intention is to modify existing, older plants to accommodate them to refuse firing. Ten candidates have been developed in Category I, five candidates in Category II.

Estimates of the performance characteristics of the candidate configurations have been calculated. This required the adoption of certain assumptions and the imposition of various design constraints. These are itemized as follows:

a. Fuel Value

(1) Refuse

Based on the information on refuse properties that was reviewed in Section II, a heating value (HHV) of 4460 Btu/lb was adopted as the probable average. The ultimate analysis considered typical for present day refuse is:

TYPICAL ULTIMATE ANALYSIS FOR REFUSE

Component	Wt-%
Moisture	27.1
Carbon	25.5
Hydrogen	3.4
Oxygen	21.7
Nitrogen	0.5
Sulfur	0.1
Inerts	21.7
Glass (9.2)	
Metals (7.1)	
Ash (5.4)	

(2) Coal

In order to avoid a cumbersome and overly complex presentation of data, combustion calculations were restricted to cases involving refuse/coal firing. Bituminous coal, of course, is the predominant fossil fuel in conventional utility use and does represent the worst case situation in terms of emissions. The performance derivations outlined herein are, however, of such a format that parallel derivations, based on oil or natural gas, can be readily obtained.

The heating value (HHV) used for coal was taken to be 12,022 Btu/lb, an average of typical values found in various source documents. The ultimate analysis for coal employed is:

TYPICAL ULTIMATE ANALYSIS FOR BITUMINOUS COAL

Component	Wt. -%
Moisture	7.8
Carbon	65.2
Hydrogen	4.5
Oxygen	7.6
Nitrogen	1.4
Sulfur	3.5
Inert	10.0

b. Refuse Charging Rate

In consideration of logistic factors, grate requirements, and other constraints, an arbitrary upper limit in refuse rate of 1000 tons per day (tpd) per unit has been observed for systems equipped with grates. Candidate designs, in which grates are not used, have been limited to inputs of 2000 tpd per unit.

A further criterion involves fuel proportions. A refuse fraction between 20% and 60%, based on heat input, has generally been sought. Diseconomies would tend to operate at lower refuse proportions, while at levels above 60% steam fluctuations would become increasingly difficult to control with the complementary fossil fuel firing-system. It should be borne in mind that the fuel fraction term applies to the energy input for a complete steam generator system. The latter may include one or more furnaces that fire straight refuse coupled with, say, a superheater firing only fossil fuel.

c. Unit Capacity

An upper limit of 500 MW has been used in deriving performance data. Four size-ranges have been defined that fit within this limitation and provide bases for the assignment of steam conditions. The upper range limits are at 40, 85, 215, and 500 MW. As discussed in the next paragraph, these ranges bracket or conform with four statistical groupings of boiler sizes within which recent boiler sales in the small and intermediate class have tended to fall.

d. Steam Conditions

As in the assignment of size ranges, steam conditions were selected that would conform with contemporary engineering practice. A survey of boiler sales for a three-year period ending in 1968 was made. It was found that four steam conditions, one within each of the size ranges, were specified for slightly over 50% of the boilers (fossil fuel fired) ordered during the period. The total number of steam conditions used (including those for nuclear plants) was 21 for the first and third year and 22 for the second year of the survey period. The four most frequently used steam conditions are listed below together with the associated size ranges. In cataloging candidate systems, these steam conditions and size ranges were applied to both the boilers and turbines.

STEAM CONDITIONS SELECTED
FOR CATALOGED SYSTEMS

Steam Conditions psig/SH, °F/RH, °F	Size of Units actually ordered, MW	Associated Size Range, MW
2400/1000/1000	235 - 650	215 - 500
1800/1000/1000	90 - 195	85 - 215
1250/950/ -	52 - 80	40 - 85
850/900/ -	20 - 26	<40

e. Other Operating Conditions

It has been assumed that an exit flue gas temperature of 450°F will be observed in order to minimize corrosion from acidic condensates. Further, 50% excess air will be employed for firing refuse and 18% for coal. Of the total air for grate-stoked furnaces, 75% will be treated as (preheated) underfire air and 25% as (unheated) overfire air. On the basis that the flue gas enters the air heater at 625°F and leaves at 450°F, the air entering at 80°F will be discharged at about 350°F, a reasonable temperature for cast iron grates now on the market.

In defining the performance parameters for the various candidate systems, no allowance has been made for the possible effects of air cleaning equipment. This is treated in a separate subsection.

2. Performance Parameters

a. Energy Requirements

Shown in Figure III-1 are representative heat rate curves for conventional plants with coal-fired units according to the selected steam conditions. Superimposed on these curves are the associated size ranges. Thus, for this design study only the solid portions of the curves are applicable. From these data the heat input to the turbine has been derived for the selected steam conditions as shown in Figures III-2 and -3.

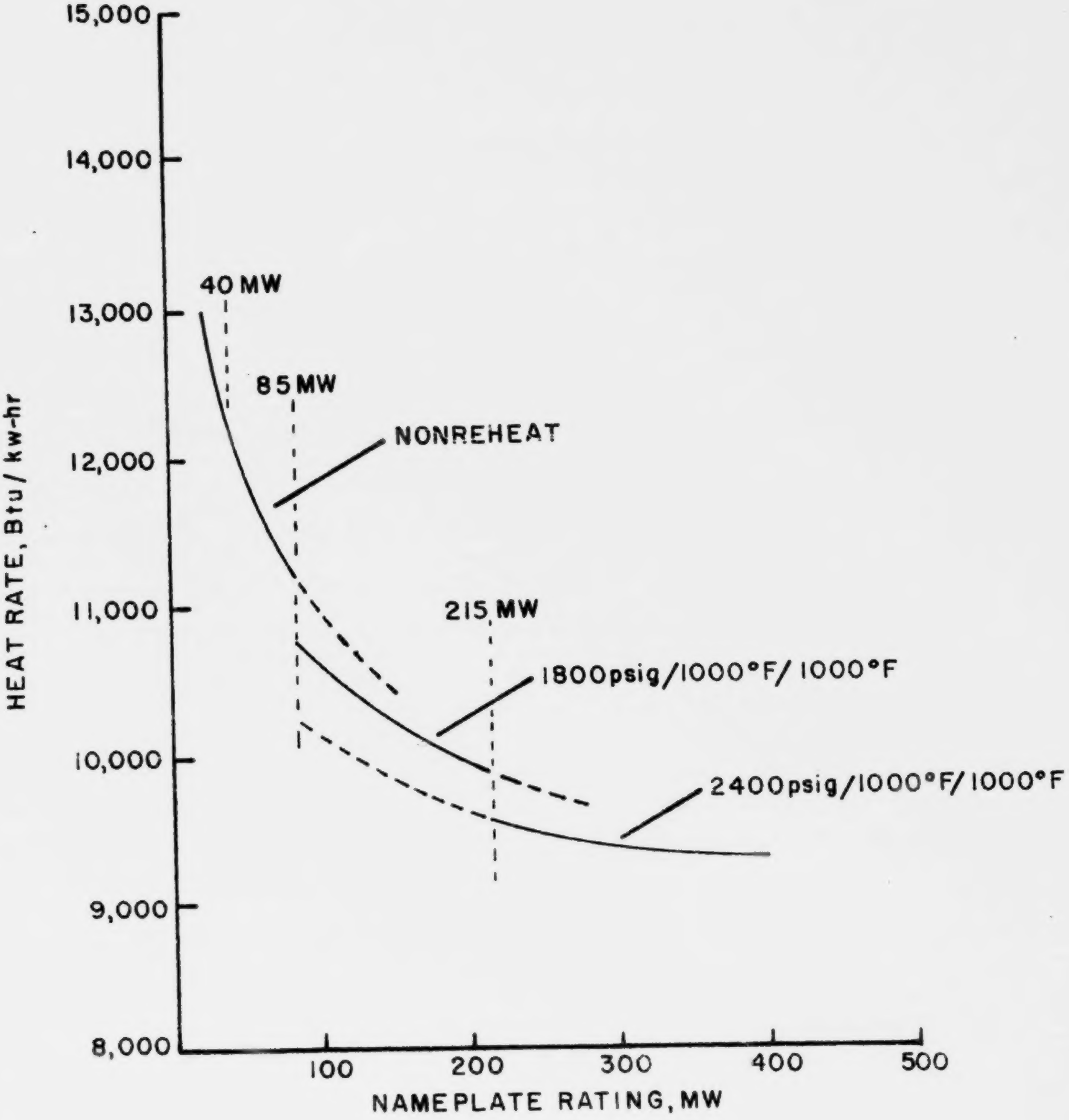


FIGURE III-1. NET PLANT HEAT RATE FOR VARIOUS STEAM CONDITIONS

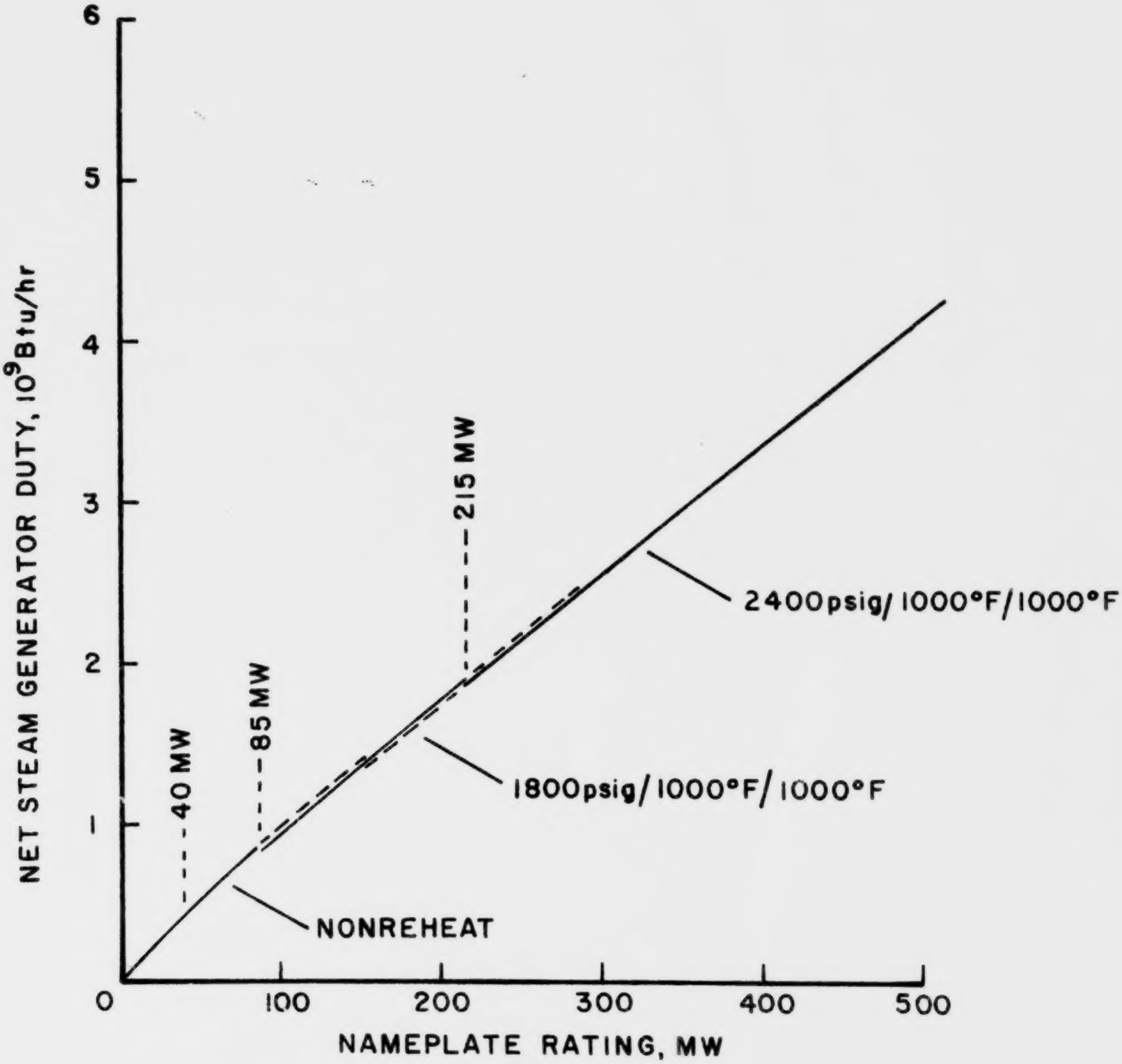


FIGURE III-2. TURBINE HEAT INPUT FOR ALL SELECTED STEAM CONDITIONS

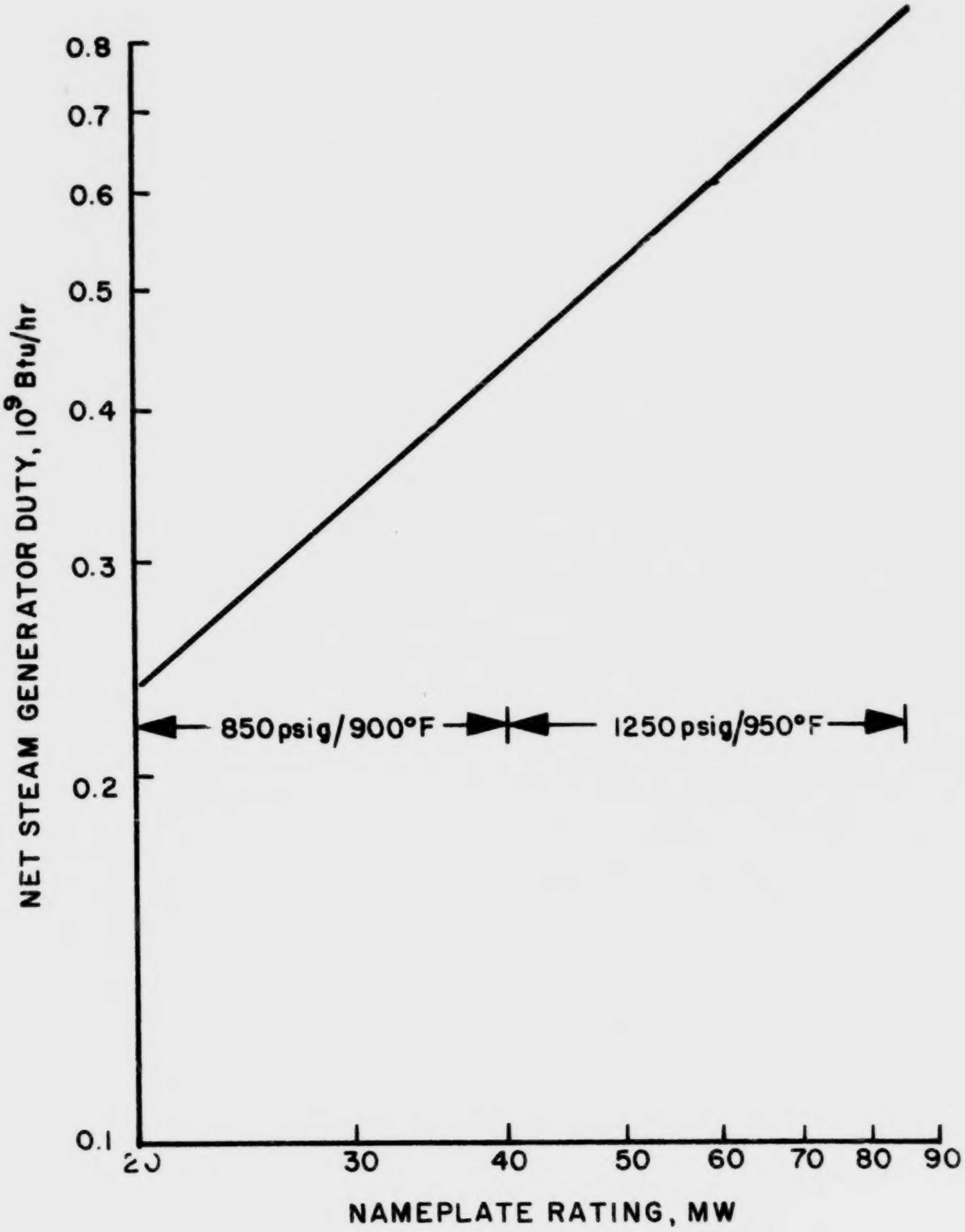


FIGURE III-3. TURBINE HEAT INPUT FOR STEAM CONDITIONS OF NONREHEAT UNITS

The heat input to the turbine is the same as the heat output of the steam generator, often referred to as "duty." The heat input to the steam generator is therefore the duty divided by the steam generator efficiency. The net plant heat rate is defined as the heat input divided by the net generation. However, for simplicity, it has been assumed that the net generation is equal to the nameplate rating. The equations employed are shown as follows:

$$\eta_{SGC} = \frac{Q_{SG\ out}}{Q_{SG\ in}} \qquad \text{(III-1)}$$

where:

η_{SGC} = Combined steam generator efficiency

$Q_{SG\ out}$ = Steam generator duty, Btu/hr

$Q_{SG\ in}$ = Steam generator input, Btu/hr

$$H_c = \frac{Q_{SG\ in}}{P_T} = \frac{Q_{SG\ out}/\eta_{SGC}}{P_T} \qquad \text{(III-2)}$$

Where:

H_c = Net plant heat rate, Btu/kw-hr

P_T = Nameplate rating, kw

By this procedure, the net turbine heat rate (H_T) has been implied in the steam generator duty in Figures III-2 and -3. By utilizing these figures, it is much simpler to vary the steam generator efficiency and calculate fuel requirements, especially with such different fuels as refuse and coal.

Having defined the relationships of the basic steam generator ratings, it is next necessary to establish the combined steam generator efficiency (η_{SGC}). This will then permit the calculation of refuse- and coal-feed requirements for the selected steam conditions and nameplate ratings, as well as such system characteristics as heat rate, flue gas volumes, and steam flow.

The combined steam generator efficiency is determined by weighting the efficiencies contributed by the individual fuels; that is:

$$\eta_{SGC} = \eta_{SGW} \times f_w + \eta_{SGF} \times (1 - f_w) \qquad \text{(III-3)}$$

where:
η_{SGW} = Steam generator efficiency with waste fuel (refuse)
η_{SGF} = Steam generator efficiency with fossil fuel (coal)
f_w = Fraction of heat input from waste (refuse)

Based on the input data of nameplate capacity (P_T), the fraction of heat input from waste (f_w), the steam generator duty ($Q_{SG\ out}$), and the steam generator efficiencies (η_{SGW} and η_{SGF}), it is possible to calculate, using Equations III-1 and -3, the required steam generator heat input ($Q_{SG\ in}$). From $Q_{SG\ in}$, the fuel input requirements can then be calculated:

$$Q_{SG\ in} = (W_w \times h_w)\, f_w + (W_f \times h_f)\,(1 - f_w) \qquad \text{(III-4)}$$

where:
W_w = Waste load (refuse), tpd
h_w = Waste fuel heat value (refuse), Btu/lb
W_f = Fossil fuel load (coal), tpd
h_f = Fossil fuel heat value (coal), Btu/lb

As specified previously, the refuse (h_w) and coal (h_f) heating values (as received) are 4460 and 12,022 Btu/lb, respectively. The only terms which are, thus far, not explicit are the steam generator efficiencies with waste fuel (η_{SGW}) and with fossil fuel (η_{SGF}). These must be determined on the basis of combustion calculations, which are explained in the following two subsections.

b. Combustion Calculations

(1) Refuse

Using the ultimate analysis listed earlier, the stoichiometric and excess combustion gas requirements were calculated to be as follows:

COMBUSTION GAS REQUIREMENTS FOR REFUSE

Constituent	Combustion Gas, lb/lb Refuse O_2	Dry Air
Carbon	0.679	2.928
Hydrogen	0.270	1.163
Sulfur	0.001	0.004
Metal, Partial Oxidation	0.010	0.042
	0.960	4.137
Oxygen	-0.217	-0.937
Total Requirement, Stoichiometric	0.743	3.200
Total Requirement, @ 50% Excess	1.115	4.800
Excess Gas	0.372	1.600

Again based on the ultimate analysis and certain of the data tabulated above, the products of combustion were calculated. The results are shown in Table III-1. The efficiency of a steam generator fired with the specified refuse composition was then calculated, as itemized in Table III-2, to give a value of 69.01%. This value was subsequently assumed to be constant for all size steam generators operated under the specified conditions.

(2) Coal

Using the heating value (12,022 Btu/lb - HHV) and ultimate analysis previously given, similar efficiency calculations were performed for the coal-fired boiler. Assuming the use of 18% excess air and a flue gas exit-temperature of 285°F, an efficiency of 88.0% was determined to be applicable for the four selected steam conditions. Based on 1% decrease of cycle efficiency for each 40°F increase in flue gas exit temperature, a steam generator efficiency of 84.0% is obtained, if the exit gas is at 450°F.

Other key data obtained in these (routine) calculations are as follows:

Component	Lb Gas/Lb of Coal 18% Excess Air	0% Excess Air
Combustion Air	11.50	9.75
Wet Flue Gas	12.55	10.77

It should be pointed out that a tubular air heater is contemplated for use in the candidate systems because of its ease of cleaning. Thus, there will be no air leakage to contend with, as with a regenerative air heater.

TABLE III-1

PRODUCTS OF REFUSE COMBUSTION

		Gas Formed per Lb Refuse		
Constituent	Derivation Factor	Lb Mol	Lb	Vol-%, Dry Basis
CO_2	$W_f^C \times M_{CO_2}/M_C$	0.0212	0.933	12.9
H_2O	(1) + (2) + (3)	(0.035)	(0.629)	-
(1) Refuse H_2	$W_f^{H_2} \times M_{H_2O}/M_{H_2}$	0.017	0.304	-
(2) Refuse H_2O	$W_f^{H_2O}$	0.015	0.271	-
(3) Comb. Air H_2O	(Note 1)	0.003	0.054	-
SO_2	$W_f^S \times M_{SO_2}/M_S$	0.00003	0.002	0.02
O_2	Excess Amount	0.0116	0.372	7.1
N_2	(4) + (5)	(0.1312)	(3.694)	(80.00)
(4)	Total Air × % N_2/100	0.1310	3.689	79.88
(5)	W_f^N	0.0002	0.005	0.02
Total Flue Gas (Wet)		0.1990	5.630	-
Total Flue Gas (Dry), G_f		0.1640	5.000	-

(Note 1). Based on standard (60% RH at 80°F) of Amer. Boiler Mfrs. Assn.

Explanation of Terms Used:

W_f = Weight fraction (per refuse ultimate analysis; superscripts designate carbon (C), moisture (H_2O), nitrogen (N), sulfur (S), and hydrogen (H_2).

M = Molecular weight; subscripts indicate specie.

TABLE III-2

REFUSE FIRED STEAM GENERATOR EFFICIENCIES

	Items	Btu/lb of Refuse	% of Heating Value
A.	Energy Utilized (specified refuse fuel value)	4460	100
B.	Heat Losses		
	1. Dry Gas, $G_f \times C_p \times (t_{lvg} - t_{air})$	443	9.93
	2. Moisture in fuel, $W_f^{H2O} (H^S_{t_{lvg}} - H^f_{t_{air}})$	330	7.40
	3. H_2O from H_2 Combustion, $W_f^{H2} (H^S_{t_{lvg}} - H^f_{t_{air}}) M_{H_2O}/M_{H_2}$	372	8.34
	4. Moisture in Air, S.H. x Lb Air/Lb Refuse x $(H^S_{t_{lvg}} - H^S_{t_{air}})$	10.6	0.24
	5. Unburned Gas, $H.V._C \times C_b \times V_{CO}/V_{CO_2}$	3.9	0.09
	6. Unburned Residue Constituents (assumed at 8%), 80% (Inert-metal) x 8% $H.V._{comb}$	79.0	1.77
	7. Sensible Heat in Residue, 80% Inert x $C_p (t_{res} - t_{air})$	34.8	0.78
	8. Unburned Fly Ash Constituents (assumed at 12%), 20% (Inert-metal) x 12% x $H.V._{comb}$	29.6	0.66

TABLE III-2 (Continued)

Items	Btu/lb of Refuse	% of Heating Value
9. Sensible Heat in Fly Ash,		
20% (Inert Metal)x C_p $(t_{lvg} - t_{air})$	3.4	0.08
Subtotal	1306.3	29.29
10. Radiation (standard estimate)		0.20
11. Unmeasured (standard estimate)		0.50
12. Manufacturer's Margin (standard estimate)		1.00
Total % Heat Loss		30.99
Steam Generator Efficiency, %		69.01

Explanation of Terms Used:

C_b = Carbon burned per lb of refuse (0.251 lb; assuming 0.004 lb is unburned).

C_p = Specific heat (Dry gas = 0.24; Residue = 0.30 Btu/lb-F°).

G_f = Lb dry flue gas/lb refuse.

H_t^S = Enthalpy of steam at t°F, Btu/lb.

H_t^f = Enthalpy of water at t°F, Btu/lb.

H.V. = Heating value: C(arbon) = 14,100 Btu/lb; comb(ustibles) in residue = 8460 Btu/lb.

S.H. = Specific Humidity, lb H_2O/lb air.

TABLE III-2 (Continued)

t_{air} = Input air temperature (assumed 80°F)

t_{lvg} = Stack gas temperature (assumed 450°F)

t_{res} = Grate residue temperature (assumed 750°F)

V = Vol-% (CO assumed at 0.02%)

W_f = Weight fraction, per ultimate analysis.

3. Operating Parameters

a. Fuel Requirements

Having determined the steam generator efficiencies, all the necessary input data are available for calculating the fuel requirements. These calculations have been made according to the format shown in Table III-3, which incorporates a sample calculation for a boiler of a nameplate rating of 400 MW. Basically, this calculation is a trial and error procedure. A flue gas exit temperature of 450°F is assumed throughout even where no refuse is burned. This has been done to establish a continuity between combined and refuse-only firing. Beginning with 0 percent refuse rate, Figure III-2 indicates a 2400/1000/1000 cycle. One turbine is applicable. The steam generator efficiency is 84.0% and the coal rate is calculated as 3960 tpd. The net plant heat rate is calculated as 9,880 Btu/kw-hr. A similar plant with a conventional steam generator efficiency would yield a net plant heat rate of 9,300 Btu/kw-hr as shown in Figure II-1. For a refuse rate of 20%, again a 2400/1000/1000 cycle would be assumed. The steam conditions and nameplate rating allow the use of one turbine and one steam generator. The net steam generator efficiency, according to Equation III-3, is 81.0%. Because the refuse rate (Item 16) is in excess of 1000 tpd, however, two steam generators would be required, each of approximately 200 MW rating. From Figure III-2, however, at 200 MW a reduction to a 1800/1000/1000 cycle will be required. At 1800 psig, according to the same figure, the maximum size for the turbine is 215 MW. Thus, for this 400 MW plant, two 200 MW turbines will be required. As shown in Table III-2, the total heat input for two 200 MW turbines is greater than for one 400 MW turbine (cf. Item 6). Because of this, the required refuse rate per steam generator again exceeds 1000 tpd. Therefore, three steam generators will be required to supply a total of 3.50×10^9 Btu/hr (cf. Item 6) or 1.17×10^9 Btu/hr per unit (cf. Item 9). A check against Figure III-2 indicates that a steam generator duty of 1.17×10^9 Btu/hr is equivalent to a 133 MW single steam generator, single turbine plant. It is shown that for three steam generators the refuse rate per steam generator is 778 tpd. Also shown is the net plant heat rate of 10,810 Btu/kw-hr.

The complete map of fuel requirements for plants of up to a nameplate rating of 500 MW are shown in Figures III-4 and -5. Each circled point represents a value calculated in the same manner as was used for the example in Table III-3. The discontinuities of Figure III-1 at changes in steam conditions also appear in Figures III-4 and -5. The number of required steam generators can be read at any point on these figures by reading the refuse rate, then dividing by 1000, and rounding off to the next higher integer.

The limits of the steam cycles in Figures III-4 and -5 are shown with dashed lines. A criterion used to develop these limits was that each steam cycle should be extended to the largest refuse rate possible. This extension is desirable because plant efficiency is sacrificed in dropping from a higher to a lower pressure steam cycle.

TABLE III-3

CALCULATION PROCEDURE FOR DETERMINING STEAM GENERATOR (S. G.) CHARACTERISTICS

Item	Parameter	Data Derivation	Nameplate Rating, MW (a)			
			400	400	400	400
1.	Refuse Rate, %	-	0	20	20	20
2.	Steam Pressure, psig	Figure III-1	2400	2400	1800	1800
3.	Number of Turbines	See text	1	1	2	2
4.	Net Turbine Rating, MW	(a)/(3)	400	400	200	200
5.	Heat Input per Turbine, 10^9 Btu/hr	Figure III-2	3.32	3.32	1.75	1.75
6.	Total Turbine Heat Input, 10^9 Btu/hr	(5)/(3)	3.32	3.32	3.50	3.50
7.	Number of S. G.'s	Figure III-2	1	1	2	3
8.	S. G. Size (approx.), MW	Figure III-2	400	400	200	133
9.	Heat Output per S. G., 10^9 Btu/hr	(6)/(7)	3.32	3.32	1.75	1.17
10.	S. G. Efficiency due to Refuse, %	Table III-2	0	69.0	6.90	6.90
11.	S. G. Efficiency due to Coal, %	See text	84.4	84.4	8.44	8.44
12.	Net S. G. Efficiency	Equation III-3	84.0	81.0	81.0	81.0
13.	Heat Input per S. G., 10^9 Btu/hr	(9)/(12)	3.96	4.10	2.16	1.44
14.	Heat Input per S. G. from Refuse, 10^9 Btu/hr	(1)/(13) x 100	0	0.82	0.43	0.29
15.	Heat Input per S. G. from Coal, 10^9 Btu/hr	100-(1)/(13) x 100	3.96	3.28	1.73	1.15
16.	Refuse Rate per S. G., tpd	2.7×10^3 x (14)	0	2210	1168	778
17.	Plant Refuse Rate, tpd	(7)/(16)	0	2210	2330	2330
18.	Coal Rate per S. G., tpd	1.0×10^3 x (15)	3960	3280	1728	1153
19.	Plant Coal Rate, tpd	(7) x (18)	3960	3280	3456	3459
20.	Net Plant Heat Rate, Btu/kw-hr	(7) x (13)/(a) x 10^3	9880	10250	10810	10810

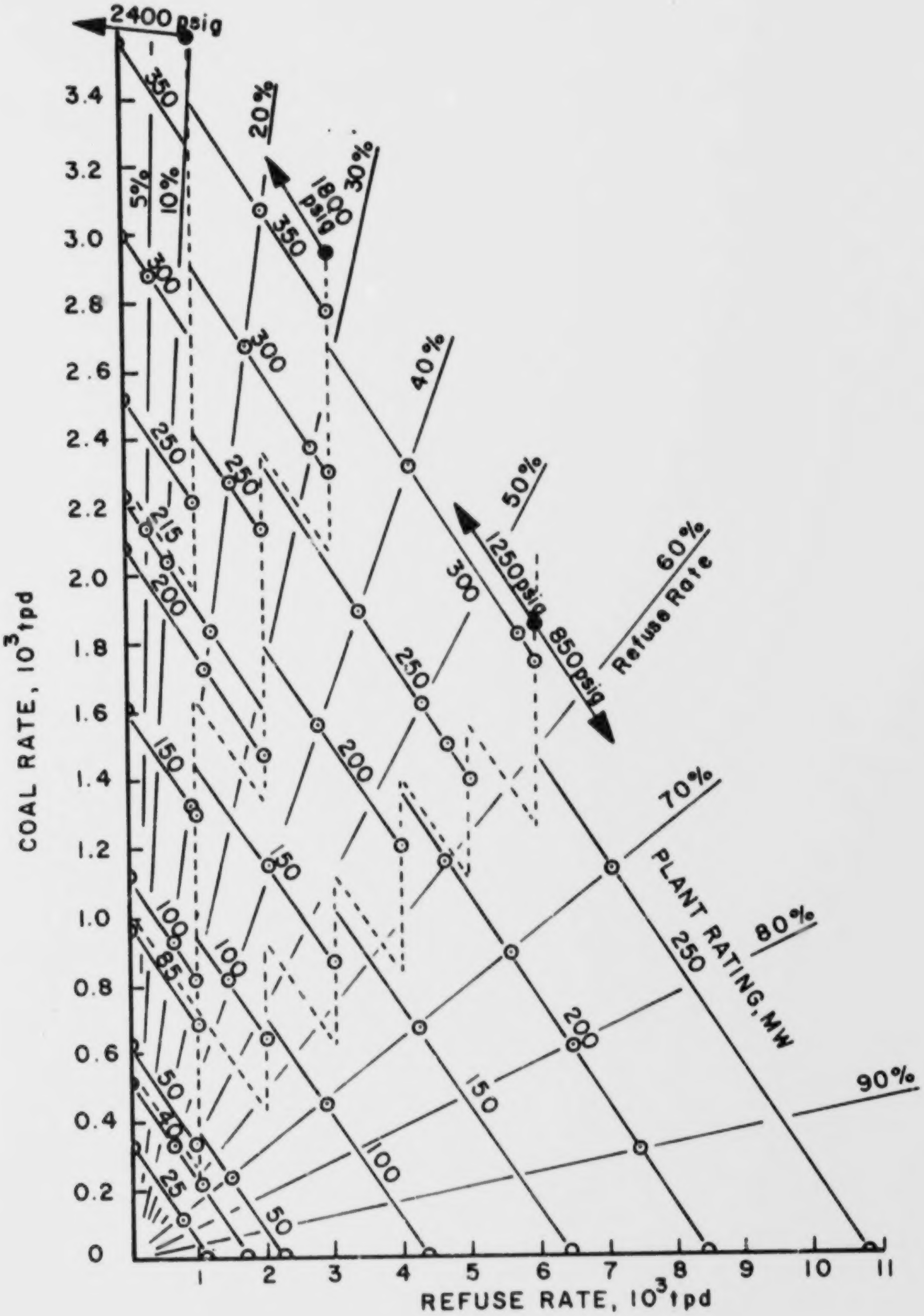


FIGURE III-4. FUEL INPUT FOR PLANTS UP TO 350 MW

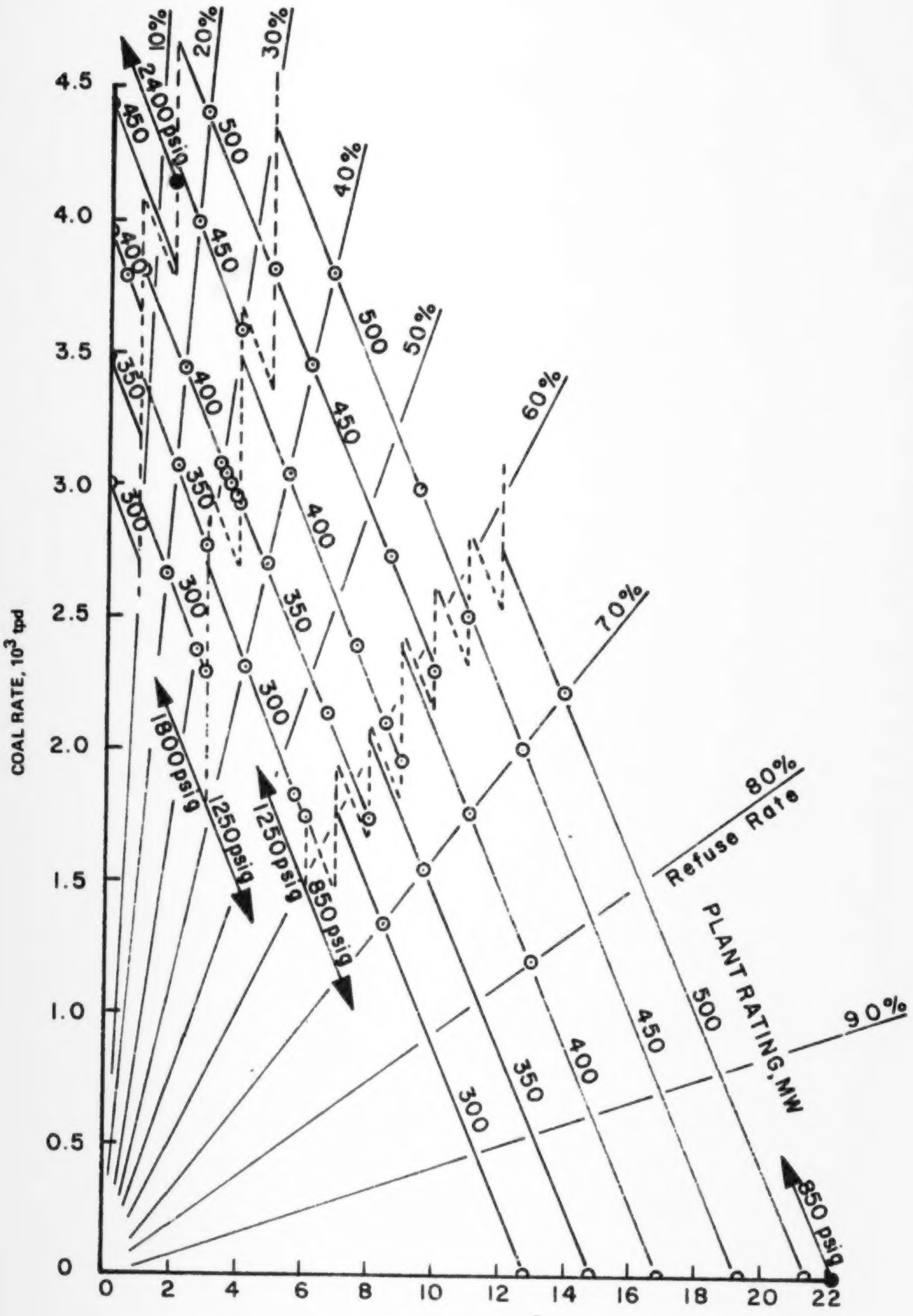


FIGURE III-5. FUEL INPUT FOR PLANTS UP TO 500 MW

For a given size plant and steam cycle, the greatest refuse rate will occur in a plant with a maximum number of steam generators. The size of the steam generators was found by determining the smallest steam generator that would be an integer divisor of the plant nameplate rating and still be within the cycle limits in Figures III-4 and -5. When the sizes of the steam generators were determined, each one was assigned a refuse rate of 1,000 tpd. The coal rate (W_f) was then calculated from the following equation, the terms and derivation of which are based on Equations III-1 through -4:

$$W_f = (Q_{SG\ out} - \eta_{SGW} W_w H_w)/\eta_{SGF} h_f \qquad \text{(III-5)}$$

b. Heat Rate

The net plant heat rate is an important parameter, because it is an indication of total plant efficiency. Using the criteria and assumptions observed in developing the power plant models, it can be shown that the net plant heat rate is a function of the individual turbine size and the fraction of heat derived from refuse. The net plant heat rate is defined by Equation III-2. In this report, steam generator duty is taken as turbine heat input. Figures III-2 and -3 show the relationship between turbine heat input and nameplate rating, the latter being assumed to be the same as net generation. The ratio of the total plant heat input to the plant nameplate rating would thus be identical to the ratio of the individual turbine heat input to the steam generator efficiency divided by the individual turbine nameplate rating. This would then mean that for any given turbine size, the net plant heat rate would be a function only of the steam generator efficiency. The combined steam generator efficiency (η_{SGC}) is a function (Equation III-3) of the fraction of heat derived from the refuse fired. Thus, a plot of net plant heat rate versus fraction of heat from refuse can be prepared using turbine nameplate rating as a parameter, as shown in Figure III-6. It was assumed that a plant using certain size turbines will have the same net plant heat rate regardless of the number of turbines that must be used.

Where shift-overs in steam conditions are involved, heat rate curves are given in Figure III-6 for both of the steam conditions. As in Table III-3, the lower steam pressure has been used for the fuel calculations. Because it was not possible to include on Figure III-6 the limits of the percent refuse that can be fired, Figures III-5 and -6 must still be used to find the range of refuse firing that is applicable for a given plant.

c. Steam Flow

In addition to fuel requirements and the resultant air and flue gas flows, another important parameter is steam flow. To retain the simplicity of the previous calculations, certain assumptions have been made in calculating steam flows. The four steam conditions selected

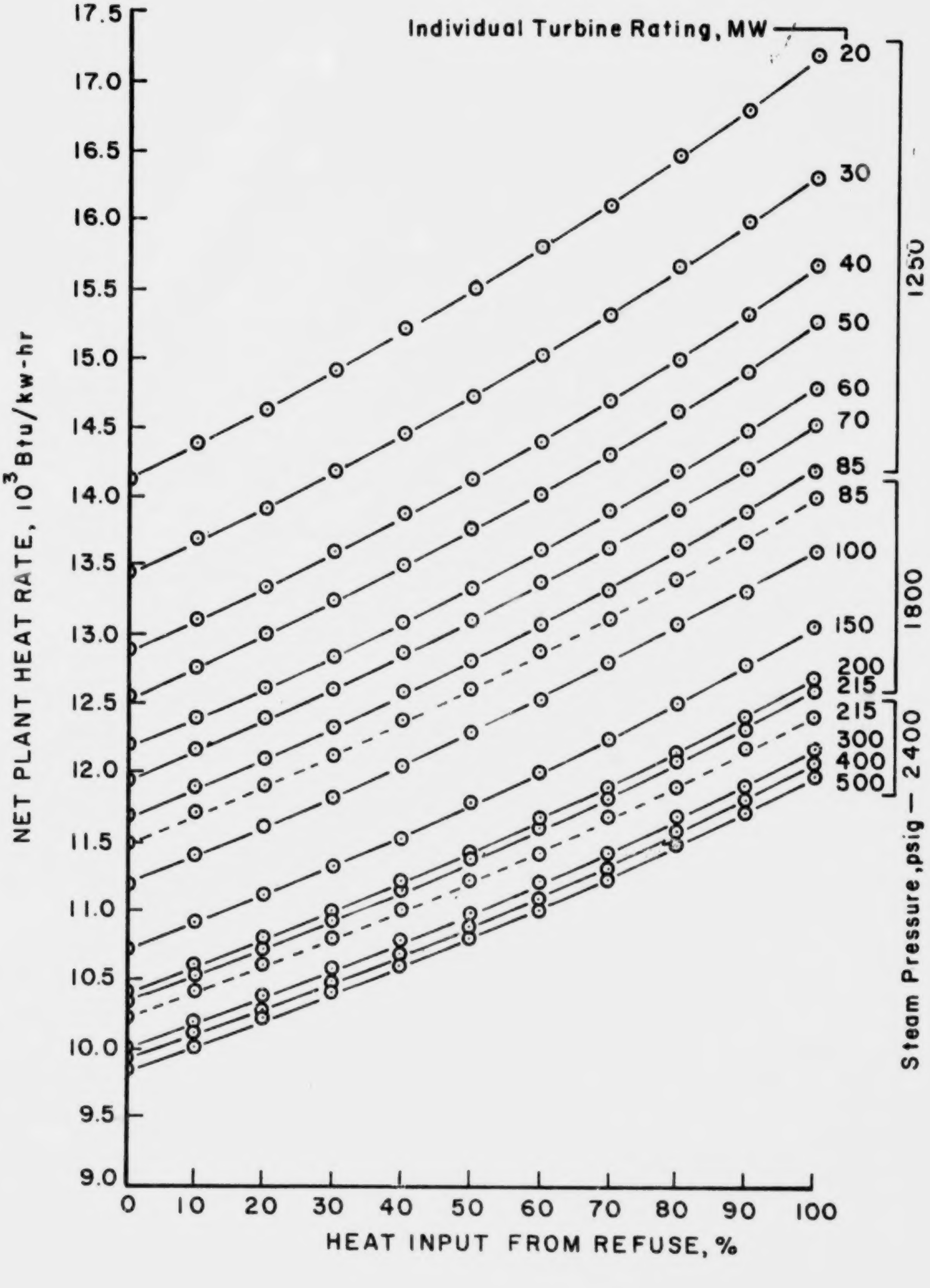


FIGURE III-6. EFFECT OF REFUSE HEAT INPUT ON NET PLANT HEAT RATE

are considered to be throttle conditions. It has been assumed that there are no losses from the steam generator outlet to the turbine throttle. However, for a plant utilizing a 2400/1000/1000 cycle, the steam generator outlet conditions would typically be 2520 psig/1005°F/1005°F. The changes in the state points are due to pressure, but this does not markedly affect the enthalpy of the system.

The steam flows have been calculated for the four steam conditions using the following equation:

$$w_S = (\Delta H_t + w_r \Delta H_r)/Q_{SG\ out} \qquad \text{(III-6)}$$

where: w_S = Steam flow, 10^3 lb/hr

ΔH_t = Enthalpy difference between turbine input steam and feedwater output, Btu/lb

w_r = Steam flow to reheater, 10^3 lb/hr

ΔH_r = Enthalpy change across reheater, Btu/lb

$Q_{SG\ out}$ = S.G. Duty, 10^9 Btu/hr.

The second term in the numerator of Equation III-6 is zero for the nonreheat steam conditions of 850/900/- and 1250/950/-. The term, ΔH_r, was derived from reheat state points typical for the other two steam conditions. Similarly, the ratio of w_r to w_S was based on practice and assumed to be typically 0.88. The value of $Q_{SG\ out}$ for various net generation rates was taken from Figure III-3. In order to avoid the complication of deriving feedwater inlet temperatures (and, thus, ΔH_t) from turbine heat balances, these temperatures were taken from the graph (Ref. 95) shown as Figure III-7.

The points chosen for calculation were those which were also employed in the fuel requirement calculations. The results of the steam-flow calculations are shown in Figure III-8.

It should be pointed out that, in cases where there are multiple steam generators and turbines, the total steam flow is not directly proportional to the nameplate rating.

In considering Figure III-8, the points of cycle change merit further comment. At 215 MW, the steam flow for the 1800 psig cycle is less than the 2400 cycle, even though the net steam generator duty is greater for the former. This occurs because the net enthalphies for the two cycles differ more than the duties. The difference in steam flows is also

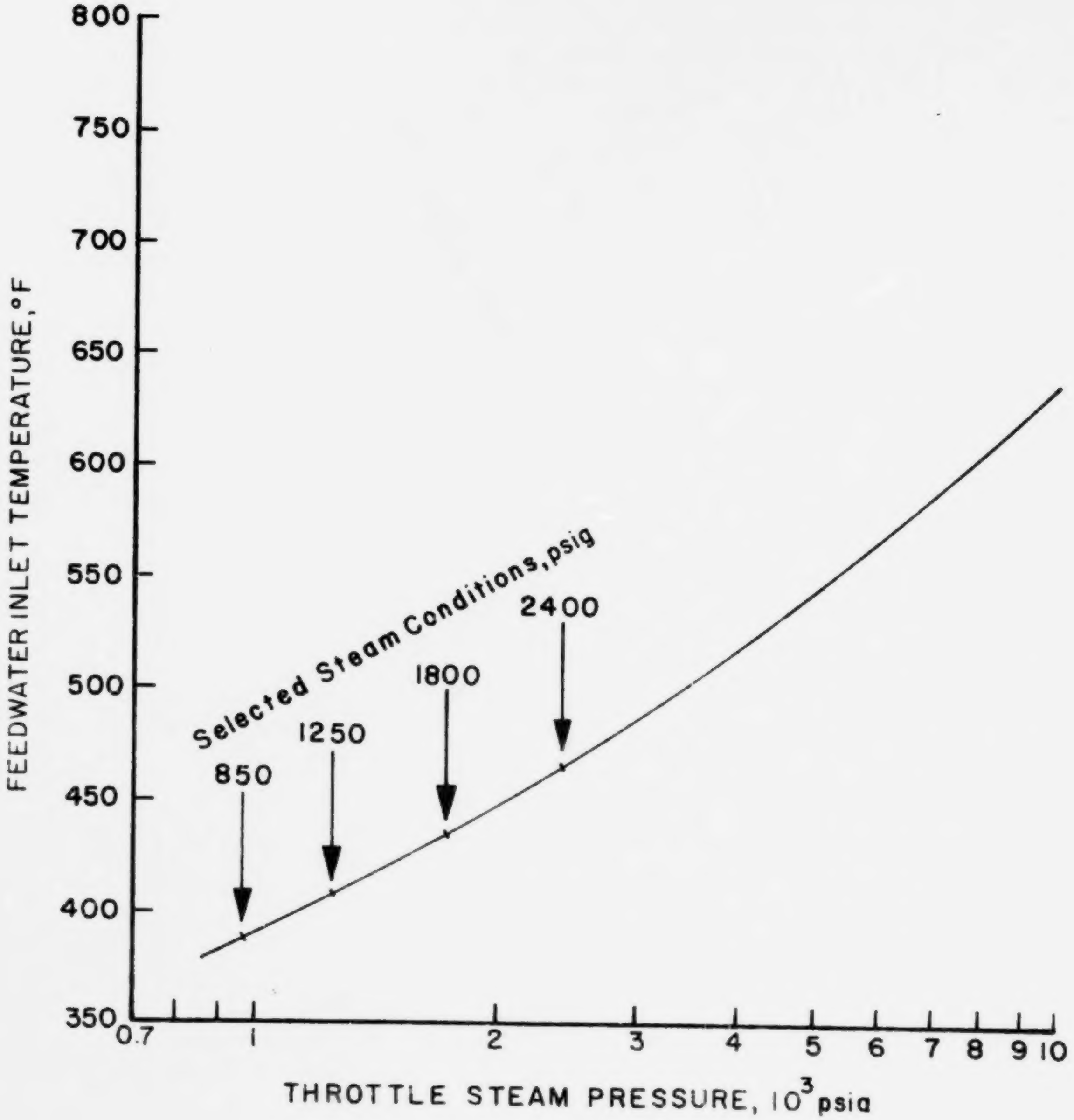


FIGURE III-7. FEEDWATER INLET TEMPERATURE

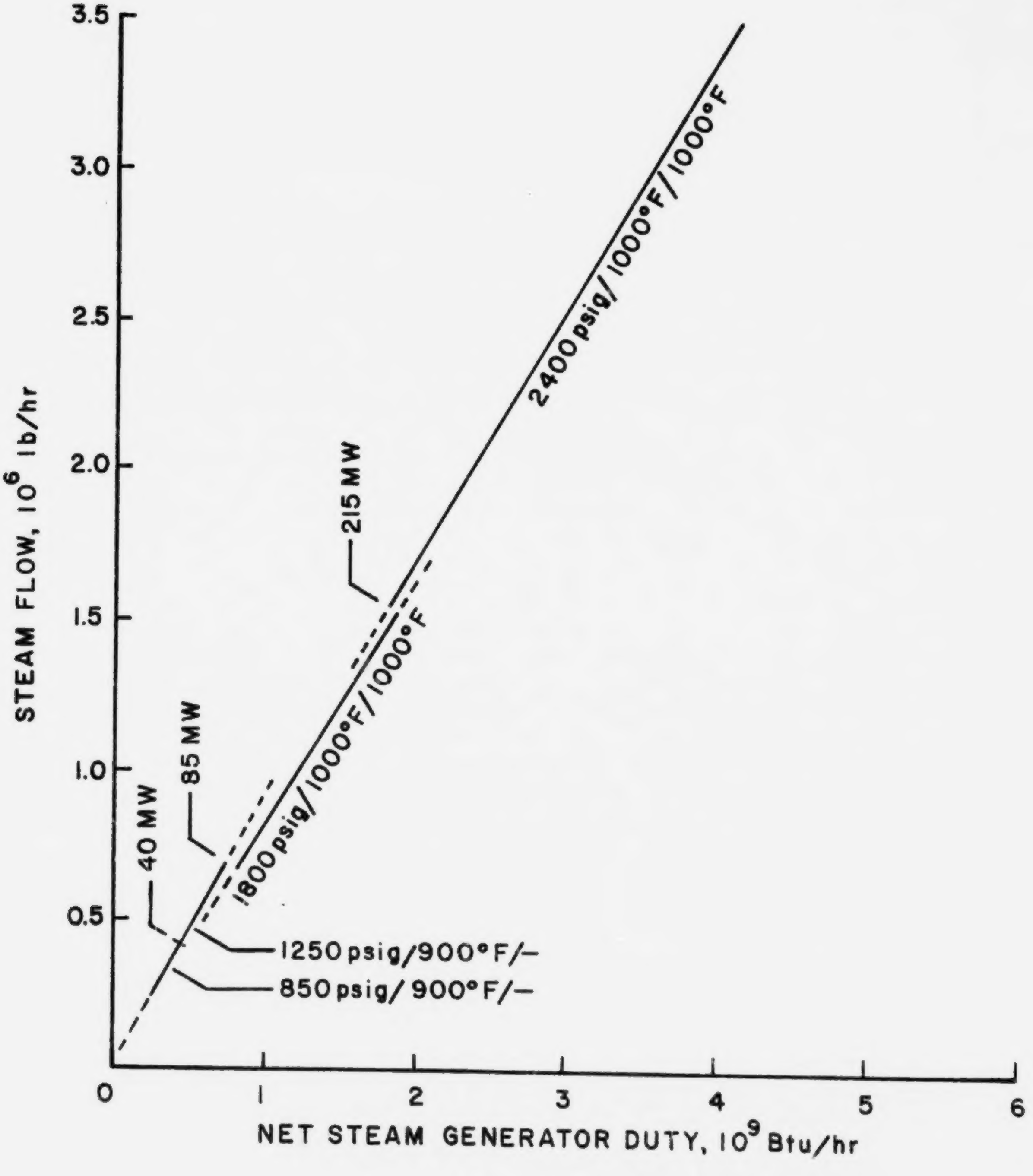


FIGURE III-8. STEAM FLOW AS A FUNCTION OF NET STEAM GENERATOR DUTY

caused by energy losses occurring elsewhere in the cycle. At 85 MW the steam flow for the nonreheat cycle is greater than for the reheat cycle. This is logical, considering that there is no reheating. At 40 MW the steam flow of the lower pressure cycle is greater. This is directly caused by the differences in net enthalpies.

4. Design Data for Candidate Systems

a. Background

For synthesizing the system possibilities, several types of steam generator arrangements have been considered. These are as follows:

Case	Designation
1	Separate Furnace
2	Combined Furnace
3	Separate Refuse-Fired Economizer
4	Saturated Steam Unit with Separate Superheater
5	Partial Superheat Unit with Separate Superheater
6	Suspension Furnace
7	Spreader Stoker
8	Slagging Furnace
9	Arch Furnace
10	Arch Furnace with Separate Superheater

Cases 1 through 4 involve the use of a conventional, agitating grate such as a backward reciprocating, forward-reciprocating, roller, or tilting grate. Cases 5 through 10 require special refuse burning equipment.

The previously calculated fuel requirements (Section III, B, 3, a) are appropriate unless otherwise noted. For most cases the excess air level for refuse is 50% and for coal 18%. Air and flue gas rates are tabulated in the appropriate sections for the various cases. The data presented is for two different plant capacities — 200 and 400 MW. The appropriate steam rating per steam generator is also tabulated.

b. Candidate System Characteristics

Case 1 - Separate Furnace. This denotes a system in which refuse and coal are fired in separate furnaces. The respective flue gases are then mixed and passed over convection sections of the steam generator, which includes an economizer and an air heater. The flue gases leave the steam generator at 450°F and enter the flue-gas cleaner. Such an arrangement was first utilized at Munich North, Block I, and, later, for two units at Stuttgart-Münster.

The schematic is shown as Figure III-9 and the summary performance calculations in Table III-4. In this and subsequent tables, the abbreviation "FG" is for flue gas. Each furnace is sized only for its design proportion of fuel. At high refuse rates some superheat surface would be suspended in the refuse furnace.

Case 2 - Combined Furnace. Designated is a system in which refuse and coal are fired in a common furnace. Such a configuration was first utilized at Munich North, Block II. In this arrangement some of the excess air supplied for refuse firing will be consumed by the coal, thereby reducing the amount of air required for the latter. The air and flue gas rates for the combined furnace can thus be set somewhat lower than for the separate furnace (Case 1). This practice was not followed during the performance tests in Munich, however, so such an adjustment has not been projected in the present design data. In any case, performance characteristics or cost would not be greatly affected by exploiting this possible benefit.

The schematic of the combined furnace is shown as Figure III-10. The common furnace would be designed for full-load heat liberation and the coal-burning equipment would be sized for full-load on coal. The performance of this system would be the same as for Case 1; the summary performance for both cases can thus be found in Table III-4.

Case 3 - Separate Refuse Fired Economizer. This system consists of two separate furnaces in which the flue gases are not combined until the gas cleaning stage is reached. In the refuse-fired furnace, feedwater is heated as in a conventional economizer. The heated feedwater is then sent to a conventional type steam generator, which is equipped with proportionately less economizer surface. Because the refuse heat output is absorbed only by an economizer, the fraction of heat that can be derived from refuse is limited. Therefore, the refuse heat input cannot be varied as for Cases 1 and 2. An arrangement of this type was first utilized at Munich South, Unit 6. At this site, the present fossil fuel used is natural gas with provision for oil- or coal-firing. The flue gases exit the respective furnaces and are mixed to lower the temperature of the dust-carrying flue gas from the refuse furnace before it enters the electrostatic precipitator.

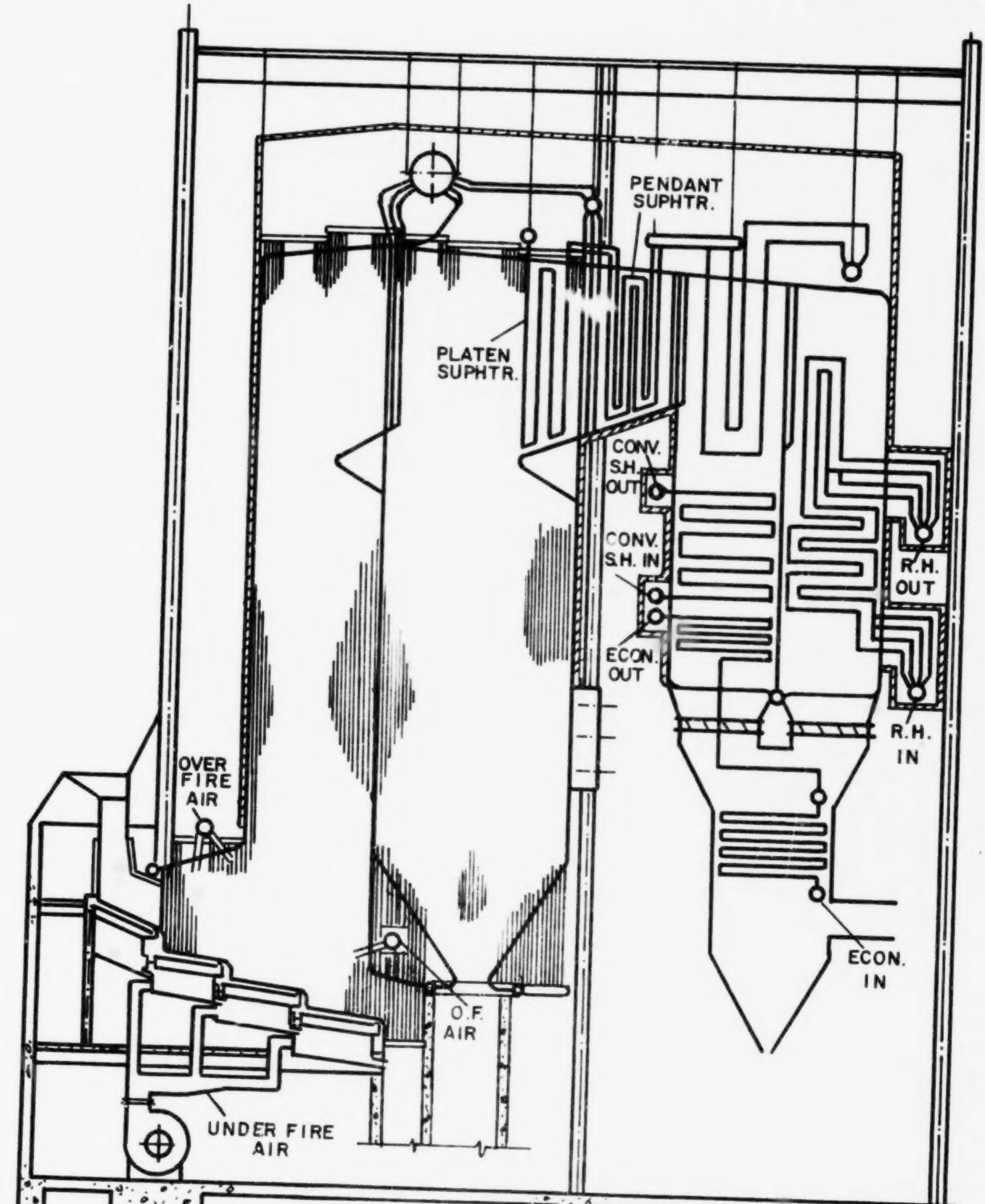

PENDANT SUPHTR.
PLATEN SUPHTR.
CONV. S.H. OUT
CONV. S.H. IN
ECON. OUT
R.H. OUT
R.H. IN
OVER FIRE AIR
O.F. AIR
ECON. IN
UNDER FIRE AIR

FIGURE III-9. CASE 1 - SEPARATE FURNACE

TABLE III-4

CASE 1 - SEPARATE FURNACE:
CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW											
	200						400					
Refuse Rate, %	0	20	40	60	80	100	0	20	40	60	80	100
Steam Pressure, psig	1800	1800	1250	850	850	850	2400	1800	1250	1250	850	850
Number of Turbines	1	1	3	5	5	5	1	2	5	5	5	10
Number of SG's	1	2	3	5	7	9	1	3	6	9	12	17
SG Duty, 10^9 Btu/hr	1.75	0.88	0.68	0.43	0.31	0.22	3.32	1.17	0.66	0.44	0.33	0.25
Steam Flow, 10^3 lb/hr	1429	715	610	400	300	220	2780	950	590	400	315	250
Refuse Rate, tpd	0	581	939	934	925	845	0	778	910	947	986	994
Coal Rate, tpd	2080	864	521	230	86	0	3960	1153	507	234	91	0
Refuse Air, 10^3 lb/hr	0	232	375	373	370	338	0	310	364	378	394	397
Coal Air, 10^3 lb/hr	1992	828	499	221	82	0	3790	1105	484	224	87	0
Total Air, 10^3 lb/hr	1992	1060	874	594	452	338	3790	1415	848	602	481	397
Refuse FG, 10^3 lb/hr	0	272	440	437	434	396	0	364	426	438	462	465
Coal FG, 10^3 lb/hr	2180	904	545	241	90	0	4140	1205	530	245	96	0
Total FG, 10^3 lb/hr	2180	1176	985	678	524	396	4140	1569	956	683	558	465
Net SG Efficiency, %	84.0	81.0	78.0	75.0	72.0	69.0	84.0	81.0	78.0	75.0	72.0	69.0
Net Plant Heat Rate, Btu/kw-hr	10,400	10,800	13,100	14,400	15,010	15,640	9,880	10,810	12,650	13,150	15,010	15,610

	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55

NOTE: Data shown are for single SG's.

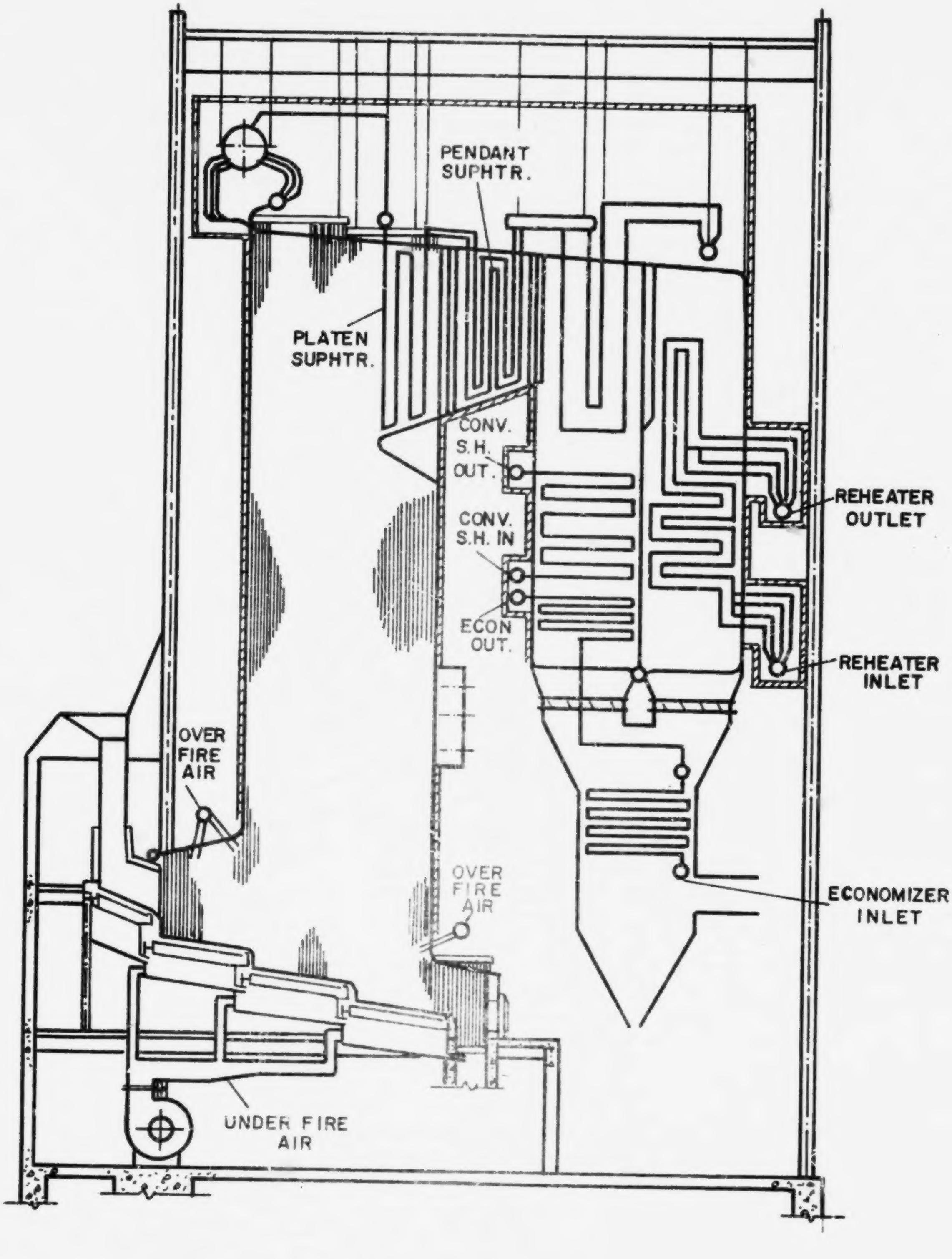

PENDANT SUPHTR.
PLATEN SUPHTR.
CONV. S.H. OUT.
CONV. S.H. IN
ECON OUT.
REHEATER OUTLET
REHEATER INLET
OVER FIRE AIR
OVER FIRE AIR
ECONOMIZER INLET
UNDER FIRE AIR

FIGURE III-10. CASE 2 - COMBINED FURNACE

The schematic of the separate refuse fired economizer is shown as Figure III-11 and the summary performance is given in Table III-5. For the plant sizes under consideration, the subcritical pressure cycle with a natural circulation steam generator is more economical than the super-critical pressure cycle with a once-through steam generator. Normally, the heated water leaving the economizer enters the steam drum where it is mixed and taken to external downcomers to headers at the lower portion of the steam generator. The water then travels upward in waterwall tubing where boiling might take place. If the feedwater entering the drum contains some steam, it can cause "carry-under" problems that can adversely affect the circulation. For this case, therefore, the maximum temperature for the economizer has been set at approximately 15°F below the saturation temperature corresponding to the drum pressure. This is shown below.

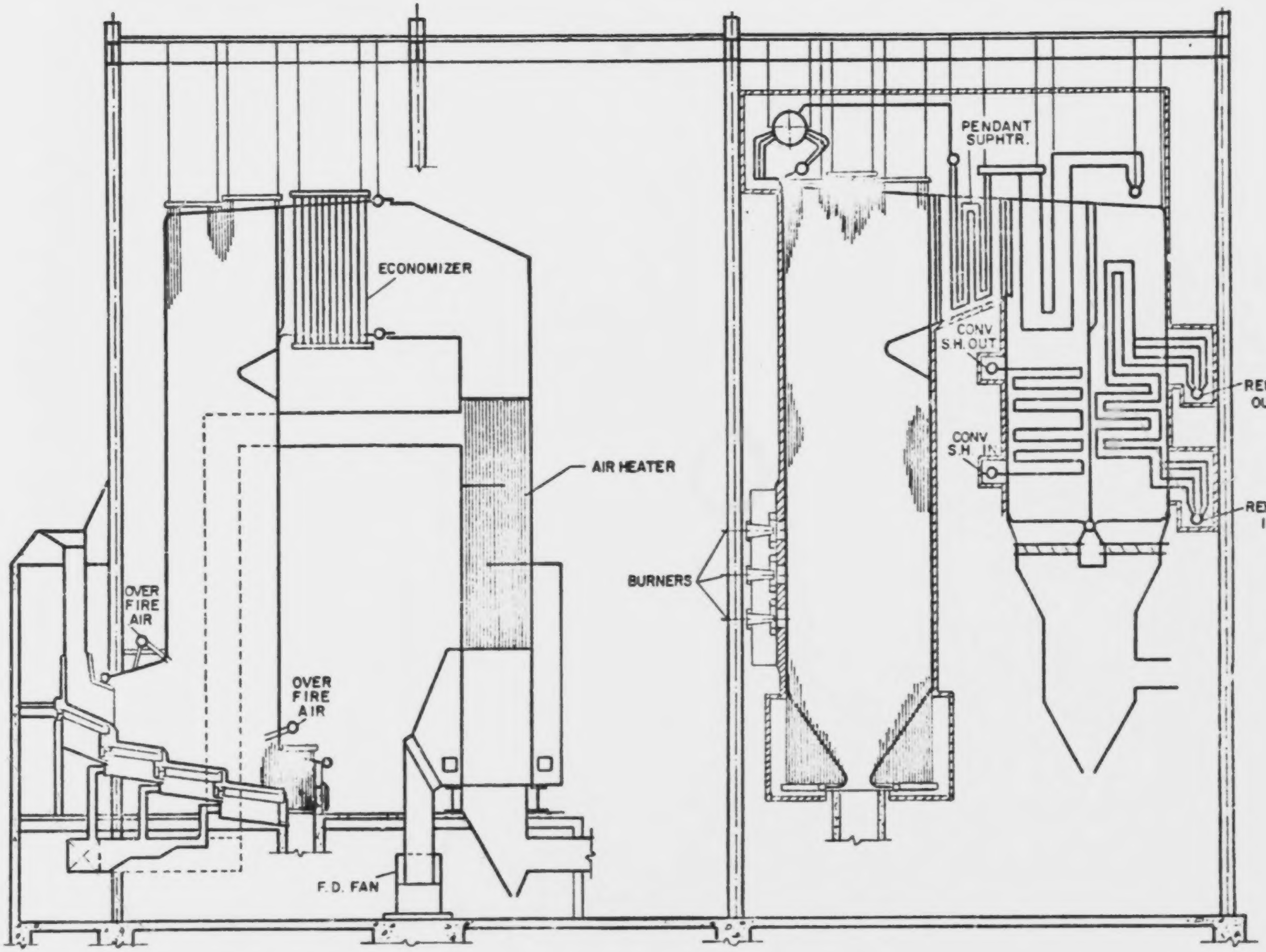
PERMISSIBLE ECONOMIZER FLUID-TEMPERATURES

Cycle Press., psig	Drum Press., psig	Sat. Temp., °F	Max. Allowable Econ. Outlet Temp., °F	Econ. Inlet Temp., °F
1800	1960	634	619	440
2400	2585	674	659	470

The economizer inlet temperature corresponds to that shown in Figure III-7. In order not to exceed the allowable economizer outlet temperatures shown above, the maximum values of heat input from refuse were found to be 16.6% and 24.0% for the 1800 and 2400 psig steam cycles, respectively.

For the separately refuse-fired economizer, the flue gas exit-temperature has been fixed at 575°F, resulting in a steam generator efficiency of 65%. The flue gas exit-temperature of the main, coal-fired, steam generator was fixed at 300°F, resulting in an efficiency of 87%. The coal-fired unit would be designed for full-load capacity in the event of loss of the refuse-fired units. When firing coal alone, the flue gas exit-temperature would have to be increased. The efficiency of the coal-fired boiler would thus be reduced in this mode of firing.

The water/steam circuit between the refuse and coal-fired steam generators would be a series connection. This would permit the use of a single coal-fired steam generator, as shown in Table III-5 for the larger plants, even though several refuse-fired economizers are required. The water circuits for the refuse-fired units would be connected in parallel in such multiple arrangements. Because only a single coal-fired boiler would be required, reheat cycles need be considered only for plants in the 85 to 500 MW range, in accordance with Tables III-1 and -2. The various temperature conditions for a plant operated in 2400 psig cycle are indicated on Figure III-12, a standard temperature-enthalpy diagram for steam and water systems.


ECONOMIZER
OVER FIRE AIR
OVER FIRE AIR
AIR HEATER
F.D. FAN
PENDANT SUPHTR.
CONV S.H. OUT
CONV S.H IN
REHEATER OUTLET
REHEATER INLET
BURNERS

REFUSE FIRED ECONOMIZER

COAL FIRED STEAM GENERATOR

FIGURE III-11. CASE 3 - SEPARATE REFUSE-FIRED ECONOMIZER

TABLE III-5

CASE 3 - SEPARATELY FIRED ECONOMIZER: CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW				
	200		400		
Refuse Rate, %	10.1	16.6 (max)	9.9	20.4	24.9 (max)
Steam Pressure, psig	1,800	1,800	2,400	2,400	2,400
Number of Turbines	1	1	1	1	1
Number of SG's (Coal/Refuse)	1/1	1/1	1/2	1/3	1/3
SG Duty, 10^9 Btu/hr	1.75	1.75	3.32	3.32	3.32
Steam Flow, 10^3 lb/hr	1,430	1,430	2,800	2,800	2,800
Refuse Rate/Econ., tpd	565	936	524	735	913
Coal Rate, tpd	1,860	1,752	3,520	3,200	3,060
Refuse Air/Econ., 10^3 lb/hr	226	375	210	353	365
Coal Air/SG, 10^3 lb/hr	1,785	1,680	3,380	3,070	2,940
Refuse FG/Econ., 10^3 lb/hr	265	440	246	344	428
Coal FG/SG, 10^3 lb/hr	1,945	1,830	369	335	322
Net SG Efficiency, %	84.5	83.4	85.0	82.8	81.4
Net Plant Heat Rate, Btu/kw-hr	10,360	10,500	9,780	10,020	10,190

	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55

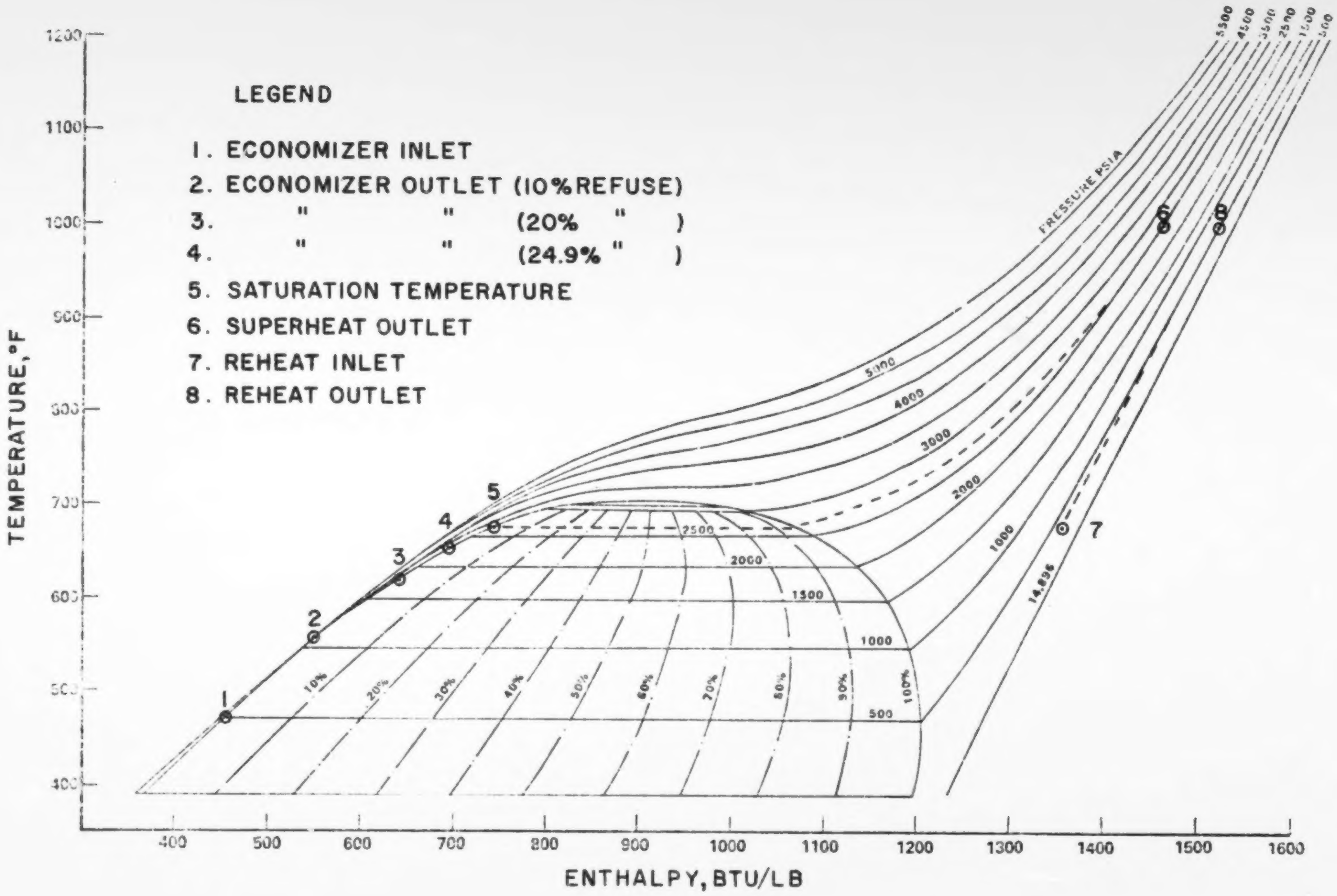


FIGURE III-12. CASE 3 - TEMPERATURE CONDITIONS FOR THE 2400 psig/1000°F/1000°F CYCLE

Case 4 - Saturated Steam Unit with Separate Superheater. This is a system in which refuse is fired to generate saturated steam, which is then delivered to a separate superheater which is fossil-fuel fired. This type of system has been considered for an "over the fence" installation in a West Coast City. The application of a separately fired superheater has been commercially applied at an East Coast utility, where the saturated steam was generated in a nuclear reactor.

The summary performance is shown in Table III-6, the schematic on Figure III-13, and the temperature conditions for the 2400 psig cycle on Figure III-14. In this arrangement, the refuse heat-input cannot be varied as was possible for Cases 1 and 2.

The flue gas exit-temperature for refuse firing was fixed at 450°F, corresponding to a steam generator efficiency of 69.0%. In the coal-fired superheater, the lowest steam temperature is approximately 670°F. Therefore, the air heater must perform the additional duty of cooling the flue gases. The temperature of the flue gas exiting from the coal-fired boiler has also been fixed at 450°F, corresponding to a steam generator efficiency for this unit of 84.0%.

The water-steam circuit is a series connection, thus permitting a single coal-fired superheater with integral reheater. Therefore, for 85 MW to 500 MW only reheat cycles need be considered.

In the Case 4 configuration, where only one refuse rate can be used for each of the steam conditions, the rate for the 1800 psig cycle (63.5%) exceeds the 60% limit previously set. The excess, however, is not considered to be sufficient to warrant the rejection of the system.

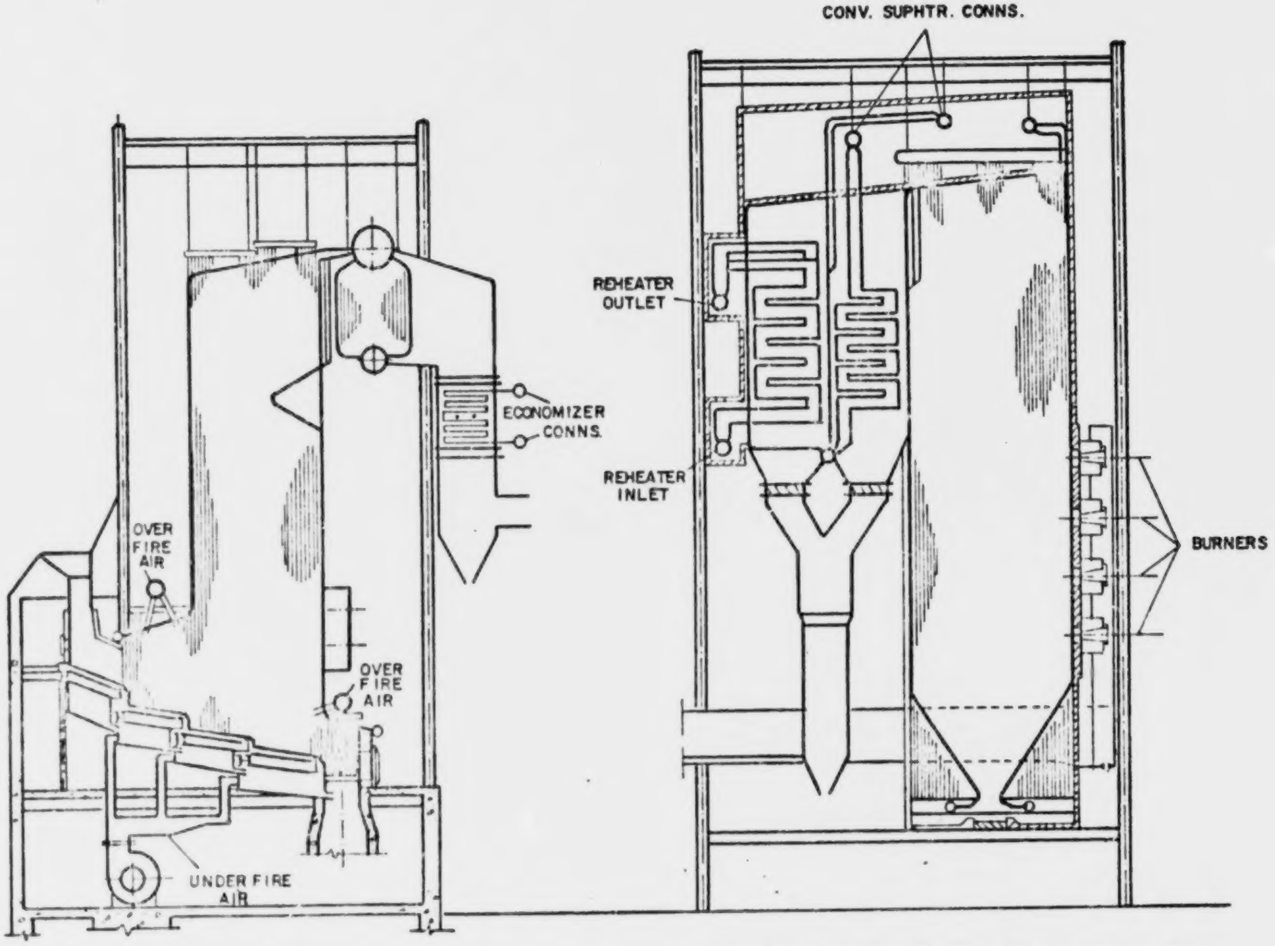
For this case, coal burners with an input capacity equivalent to 10% of full load would be installed in the refuse units for trimming control. It has been assumed that the coal could be taken from the mills used to feed the separately fired superheater. It should also be noted that, because multiple refuse units would be required, the variations in steam flow could be minimized by manifolding the several steam inputs before they enter the coal fired superheater.

Case 5 - Partial Superheat Unit with Separate Superheater. This system is similar to Case 4 except that partial superheating is provided in the refuse furnace. A proprotionately greater amount of heat input can thus be derived from refuse, although the amount is again limited by the cycle. The steam is partially superheated in the refuse-fired steam generator to a temperature of 750°F as shown on Figure III-15. In the interest of avoiding fly-ash corrosion problems, this steam temperature has been observed as the upper limit for all separately-fired refuse systems. This could not of course be applied in those cases wherein both coal and refuse are fired in the same boiler.

TABLE III-6

CASE 4 - SEPARATE FOSSIL FUEL SUPERHEATER (SATURATED STEAM INPUT): CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW	
	200	400
Refuse Rate, %	63.5	58.3
Steam Pressure, psig	1800	2400
Number of Turbines	1	1
Number of SG's (Coal/Refuse)	1/5	1/7
SG Duty, 10^9 Btu/hr	1.75	3.32
Steam Flow, 10^3 lb/hr	1430	2800
Refuse Rate/SG, tpd	806	878
Coal Rate, tpd	857	1840
Refuse Air/SG, 10^3 lb/hr	323	352
Coal Air, 10^3 lb/hr	822	1764
Refuse FG/SG, 10^3 lb/hr	388	412
Coal FG, 10^3 lb/hr	898	1928
Net SG Efficiency, %	74.5	75.3
Net Plant Heat Rate, Btu/kw-hr	11,745	11,000
	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55


CONV. SUPHTR. CONNS.
REHEATER OUTLET
REHEATER INLET
ECONOMIZER CONNS.
BURNERS
OVER FIRE AIR
OVER FIRE AIR
UNDER FIRE AIR

REFUSE FIRED STEAM GENERATOR

SEPARATE FOSSIL FUEL FIRED SUPERHEATER
(SATURATED STEAM)

FIGURE III-13. CASE 4 - SATURATED STEAM UNIT WITH SEPARATE SUPERHEATER

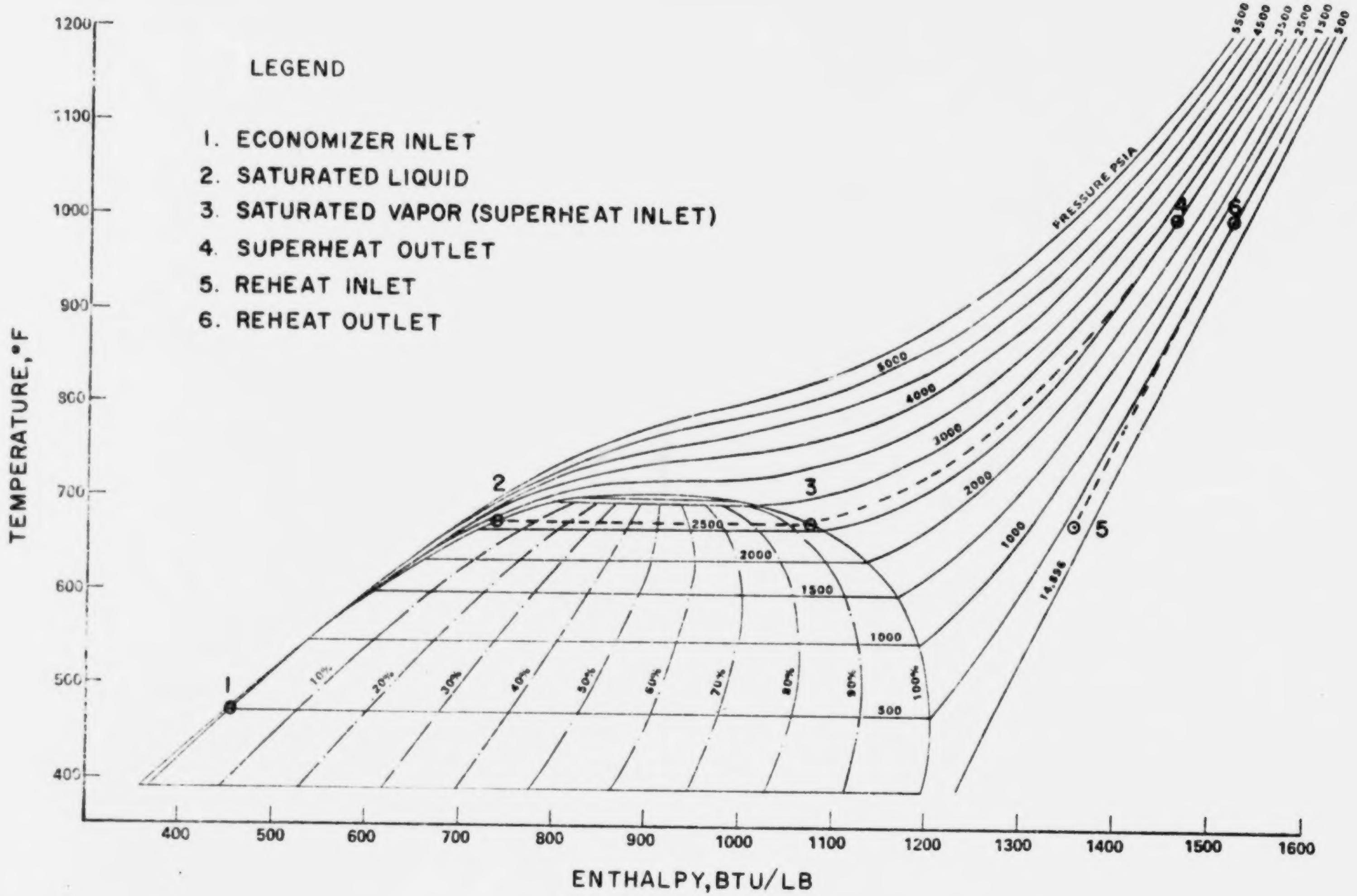


FIGURE III-14. CASE 4 - TEMPERATURE CONDITIONS FOR THE 2400 psig/1000°F/1000°F CYCLE

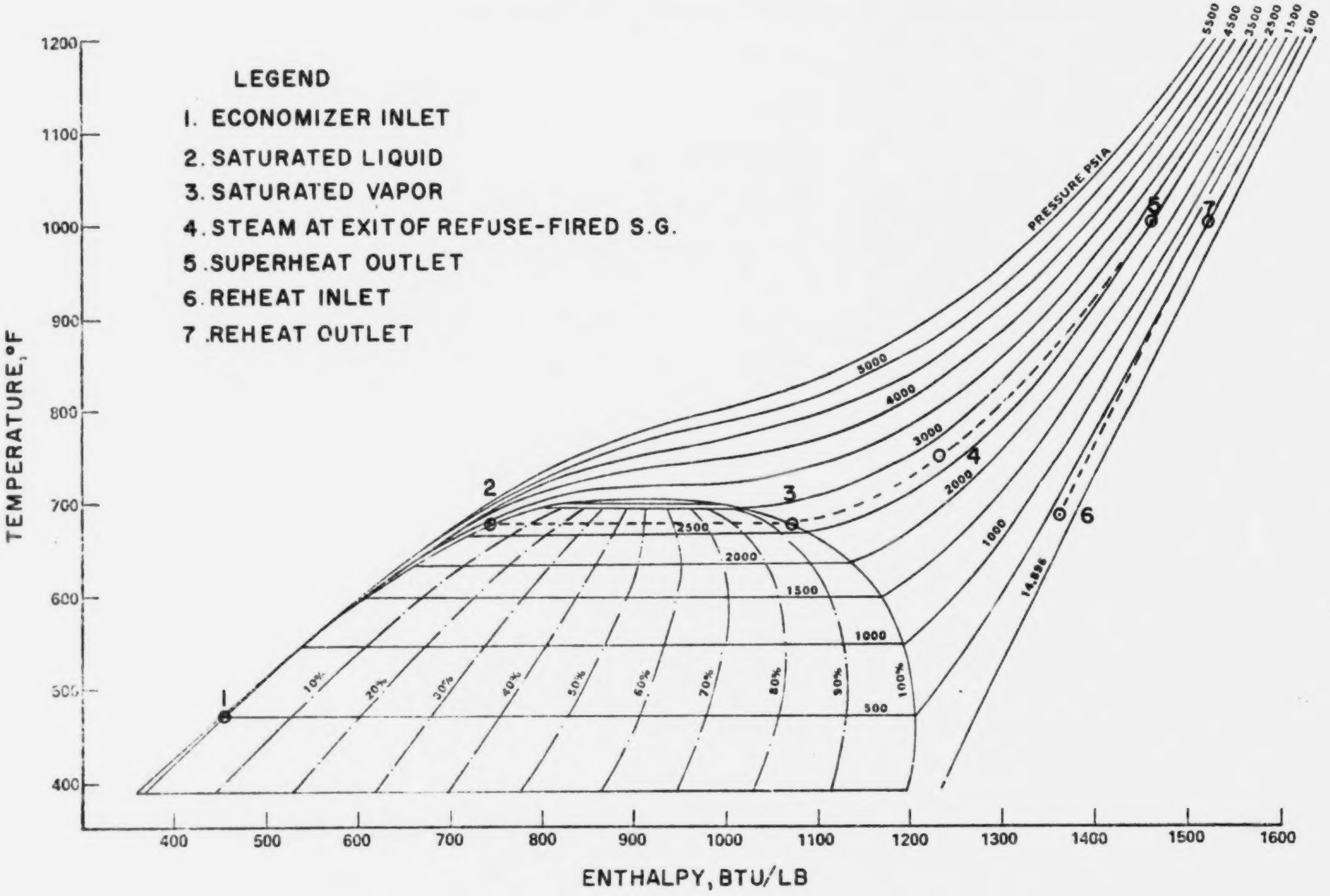


FIGURE III-15. CASE 5 - TEMPERATURE CONDITIONS FOR 2400 psig/1000°F/1000°F CYCLE

Under Case 5 conditions, the heat input from refuse would represent about 75% of the total. This would probably lead to steam flow variations that would be too great to be considered for large power-generating plants.

As in all the cases thus far discussed, it has been assumed for Case 5 that refuse would be burned on a reciprocating grate with refuse-conditioning provided only for bulky refuse. This type of burning is actually the cause of the thermal variations that result in steam-pressure fluctuations. In order, therefore, to consider this case, a system modification was introduced wherein more homogenous burning would obtain. This was done by substituting a spreader stoker for the agitating grate.

This firing configuration was initially planned for and has been incorporated into Case 7, which is definitively labelled a "spreader stoker." The boiler arrangements for Cases 5 and 7 are, otherwise, quite different. One can, however, refer to Case 7 for further details on the firing principle that is common to both.

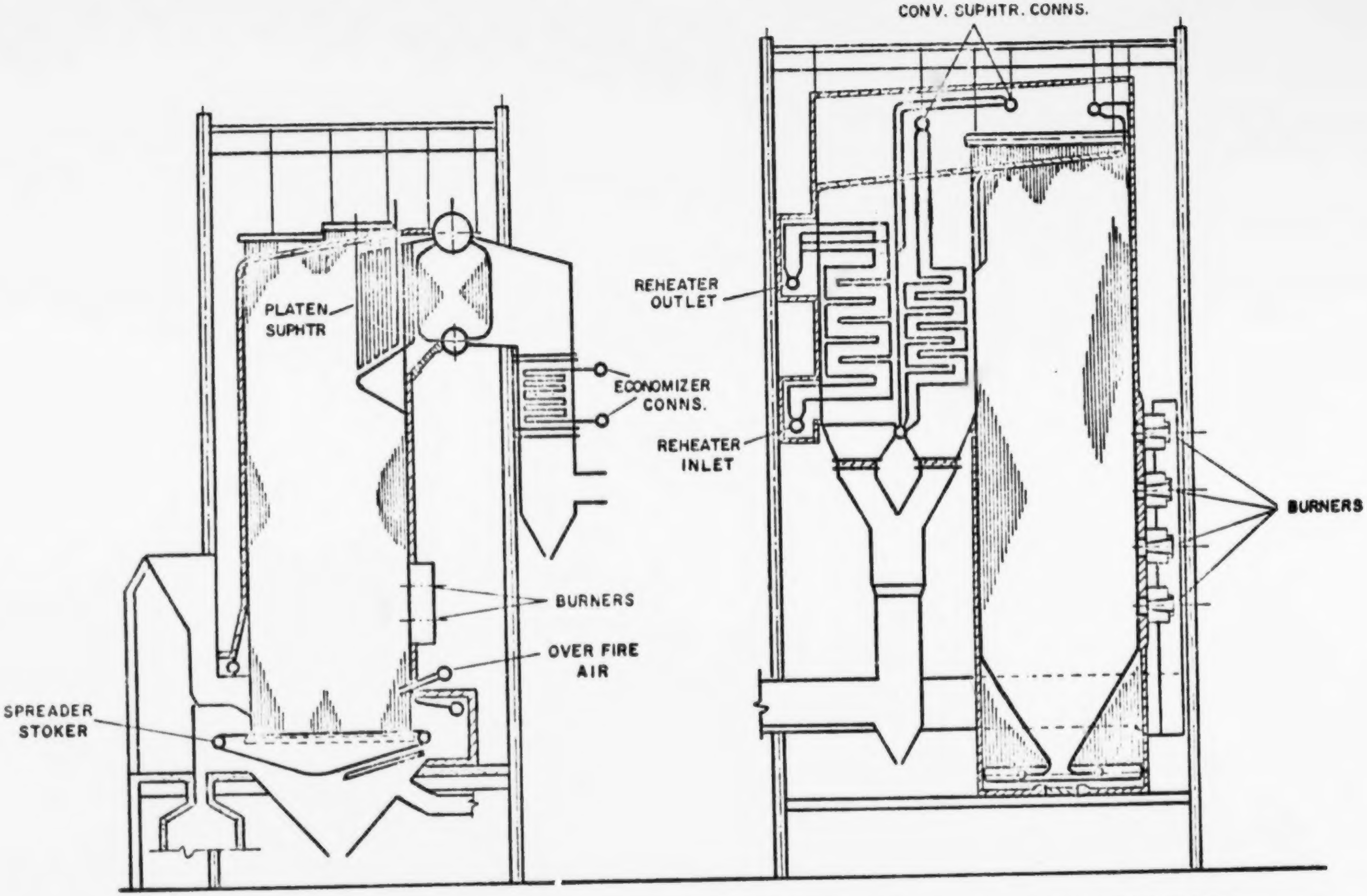
The Case 5 schematic, as revised, is shown in Figure III-16. A summary of the performance calculated for this case is presented in Table III-7.

Case 6 - Suspension Furnace. This is a conventional (pulverized-coal-firing type) furnace to which 2-in. nominal sized refuse is instead delivered and fired. It has been suggested (Ref. 41) that most of the refuse will burn while falling to the bottom of the furnace. The remaining, unburned refuse would be burned on a dumpgrate. This type of arrangement is being constructed by an East Coast industrial plant for firing industrial refuse.

The overall performance can be considered to be the same as for Cases 1 and 2 (Table III-4), although, in suspension firing, one might realize better burn-out and can expect some fuel dehydration due to size-reduction operations. Because data is not available at this time, the possible benefits of such effects could not be reflected in the performance calculations. The schematic is shown in Figure III-17.

This suspension-firing case is essentially the same as Case 2, combined furnace, in terms of boiler configuration. For Case 6, however, the furnace would have to be taller in order to optimize the degree of burning achieved while the refuse is suspended. This case is considered in further detail in the section on Retrofit plants (Modification No. 5).

Case 7 - Spreader Stoker. This is a furnace to which 4-in. nominally sized refuse is delivered and fired. The mechanism of stoking is based on a pneumatic system which blows the refuse into the furnace where


CONV. SUPHTR. CONNS.
PLATEN SUPHTR
REHEATER OUTLET
ECONOMIZER CONNS.
REHEATER INLET
BURNERS
BURNERS
OVER FIRE AIR
SPREADER STOKER

REFUSE FIRED STEAM GENERATOR
(SPREADER STOKER)

SEPARATE FOSSIL FUEL FIRED SUPERHEATER
(SUPERHEATED STEAM)

FIGURE III-16. CASE 5 - PARTIAL SUPERHEAT UNIT WITH SEPARATE SUPERHEATER

TABLE III-7

CASE 5 (REVISED) - SEPARATE FOSSIL FUEL-SUPERHEATER (PARTIALLY SUPERHEATED STEAM INPUT): CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW	
	200	400
Refuse Rate, %	75.5	71.3
Steam Pressure, psig	1800	2400
Number of Turbines	1	1
Number of SG's (Coal/Refuse)	1/5	1/9
SG Duty, 10^9 Btu/hr	1.75	3.32
Steam Flow, 10^3 lb/hr	1430	2800
Refuse Rate/SG, tpd	983	915
Coal Rate, tpd	587	1302
Refuse Air/SG, 10^3 lb/hr	393	366
Coal Air, 10^3 lb/hr	563	1248
Refuse FG/SG, 10^3 lb/hr	461	428
Coal FG, 10^3 lb/hr	600	1362
Net SG Efficiency, %	72.6	73.4
Net Plant Heat Rate, Btu/kw-hr	12,035	11,330

	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55

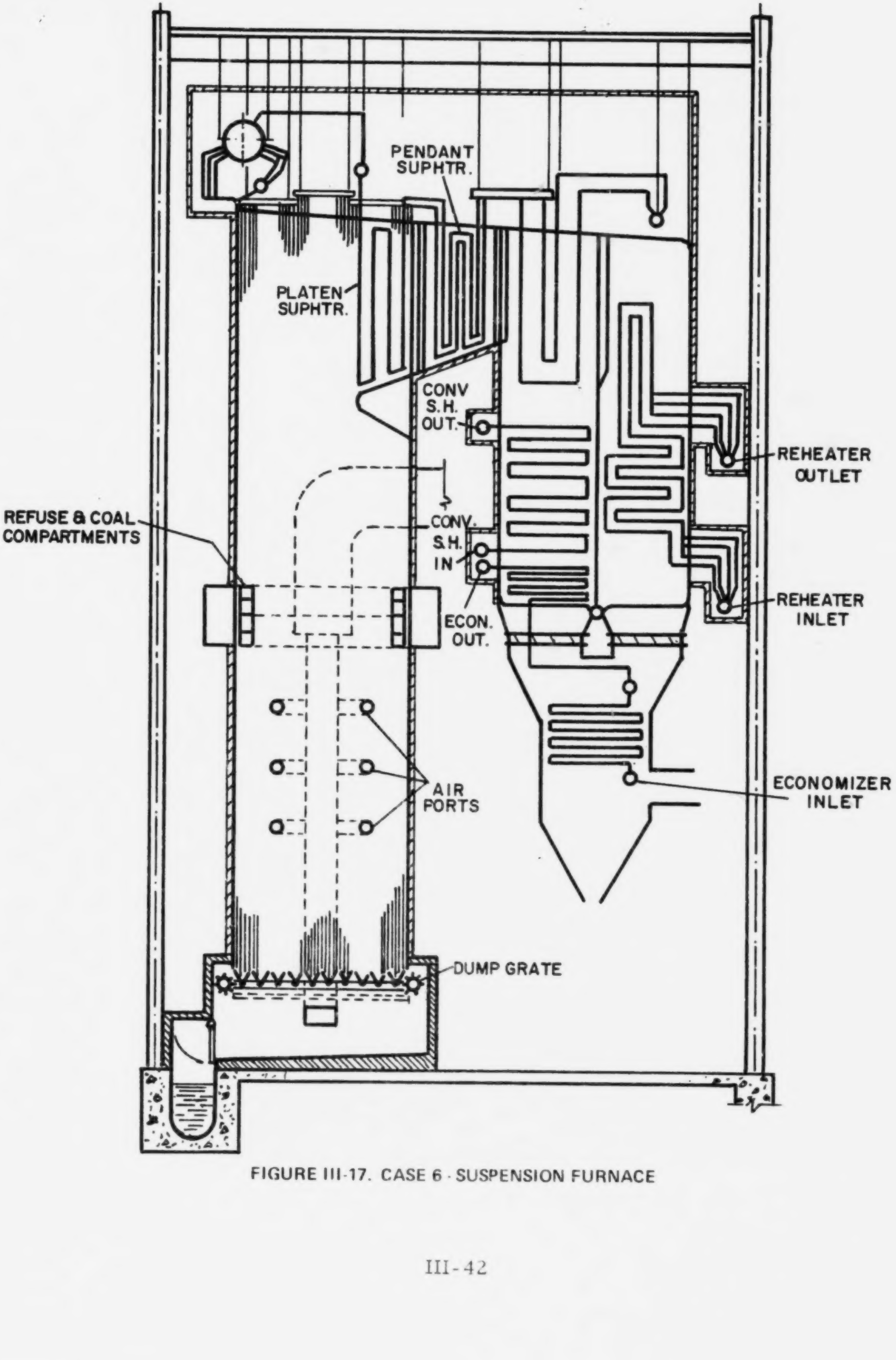

PENDANT SUPHTR.
PLATEN SUPHTR.
CONV S.H. OUT.
REHEATER OUTLET
REFUSE & COAL COMPARTMENTS
CONV. S.H. IN
ECON. OUT.
REHEATER INLET
ECONOMIZER INLET
AIR PORTS
DUMP GRATE

FIGURE III-17. CASE 6 - SUSPENSION FURNACE

it burns as it falls through the flame and spreads over the length of a travelling grate. Such an arrangement will be utilized at a Canadian municipal plant, which will fire refuse exclusively.

The schematic for this system is shown in Figure III-18. The overall performance is considered to be the same as for Cases 1 and 2 (Table III-4), although, as with Case 6, a certain degree of performance enhancement may be available.

Aside from the firing mode, the boiler configuration of the spreader stoker may be regarded as the same as that of Case 2. For Case 7, the coal would not be burned on the grate, but in pulverized form, in suspension. In general, pulverized coal firing is more efficient and yields more uniform heat liberation. Since the steam generated would be for power production, the additional pulverizers and coal burners would be justified.

Case 8 - Slagging Furnace. In this furnace, shredded refuse is delivered and fired together with pulverized coal. The firing conditions are such that a pool of slag forms at the bottom of the furnace. The schematic is shown in Figure III-19. The overall performance can be considered to be the same as for Cases 1 and 2 (Table III-4), and the configuration, aside from method firing, the same as that of Case 2. The slag-tap furnace will require prior conditioning of refuse to a nominal two-inch top size. This scheme offers the desirable feature of producing a compact residue of high density, which is easily disposed of or can be marketed.

Although slagging furnaces are still used in Europe, they have not found favor in domestic use. The availability (plant factor) of slagging furnaces is lower than dry-bottom units. Maintenance is also a serious problem. In operation, the turn-down is limited due to the necessity of maintaining a molten slag. Utilization of the slagging furnace in combination with refuse has been studied in Europe and to a limited extent in a domestic pilot plant. The Munich Electricity Works seriously considered this type of unit but abandoned it as being technically risky. Their experience and recommendations should not be overlooked.

The most important fuel property to be considered relative to this system is the melting temperature of the mixed refuse/coal ash. As pointed out in Section II, B, considerable doubt exists as to whether slagging conditions could be promoted on a continuing basis, in view of the probable high variability in the residue properties. On this basis, this case must be regarded as having some serious technical drawbacks. It is further felt that the refuse rate should be limited to a maximum of 40% of the heat input. On this provisional basis, this case has been included in the design data and capital cost analysis.

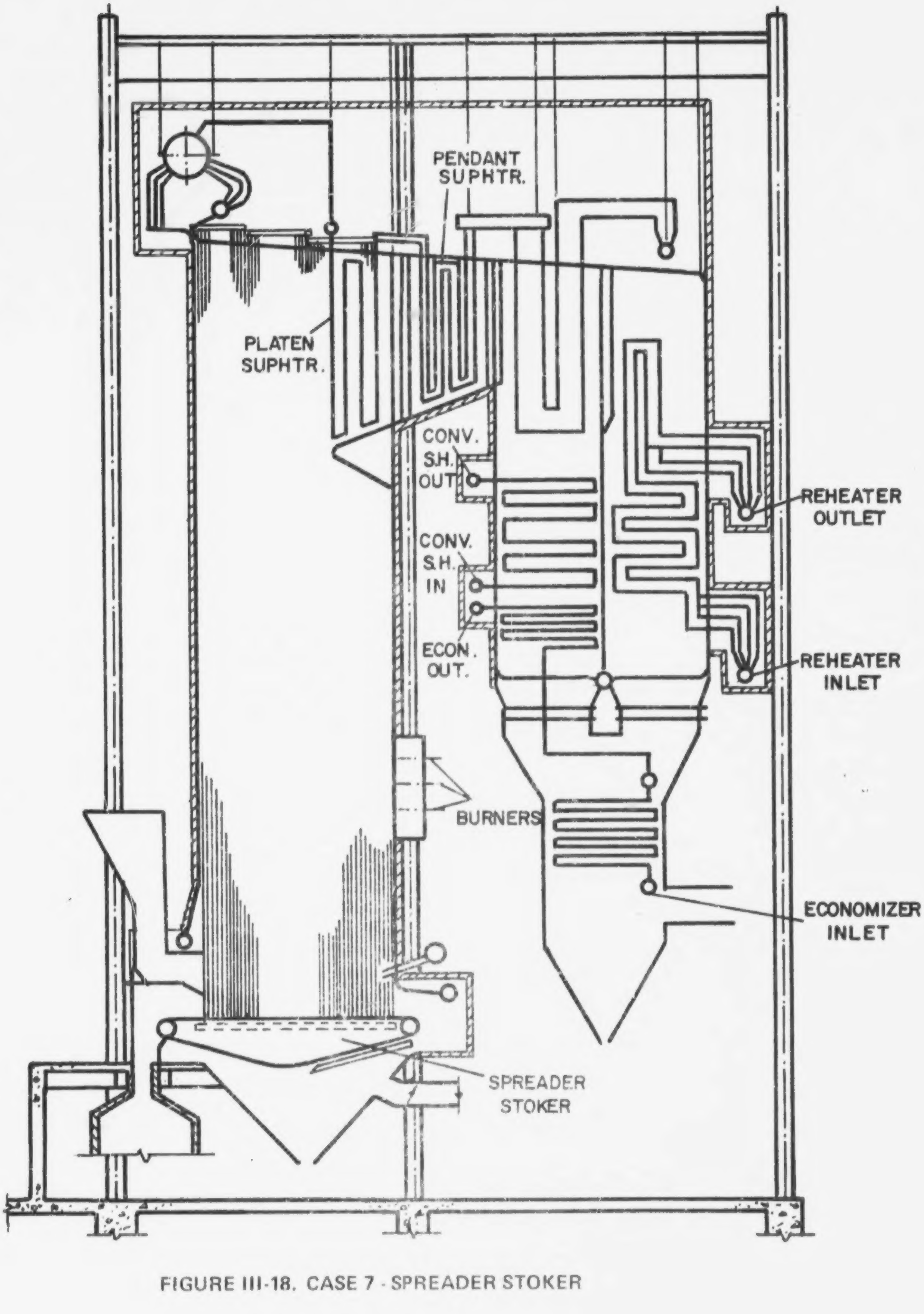

PENDANT SUPHTR.
PLATEN SUPHTR.
CONV. S.H. OUT
REHEATER OUTLET
CONV. S.H. IN
ECON. OUT.
REHEATER INLET
BURNERS
ECONOMIZER INLET
SPREADER STOKER

FIGURE III-18. CASE 7 - SPREADER STOKER

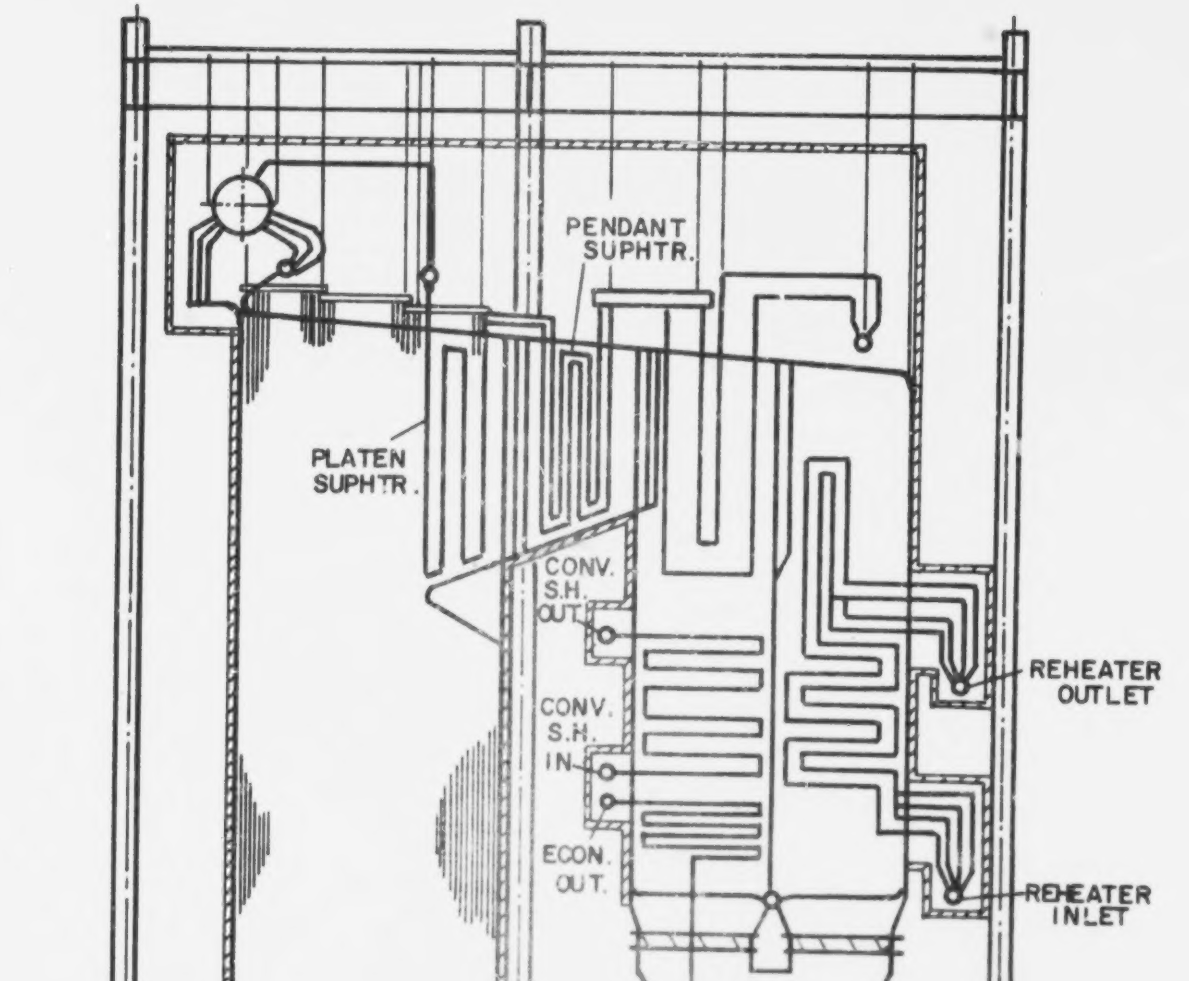

PENDANT SUPHTR.
PLATEN SUPHTR.
CONV. S.H. OUT.
REHEATER OUTLET
CONV. S.H. IN.
ECON. OUT.
REHEATER INLET
COAL
REFUSE
COAL
REFUSE
ECONOMIZER INLET
AIR PORTS
SLAG TAP
MOLTEN SLAG

FIGURE III-19. CASE 8 - SLAGGING FURNACE

Case 9 - Arch Furnace. This is a system in which combined suspension firing is practiced, but without the use of a dump grate. This type of furnace is also discussed in Appendix B (Section III, A, 4, a). The expected advantage of employing a system of this type would be a high stoking-rate. In the previous cases discussed, the refuse rate was limited to 1000 tpd, which is about the maximum capacity for any type of grate available at the present time or in the immediate future. In fact, only one manufacturer has a grate of this size in operation. This is a backward reciprocating grate in use at the Munich plants (North - Unit 2; South - Unit 5).

Because of the absence of the restriction on refuse-rate imposed by the grate, calculations for the present case were based on an upper fuel rate of 2000 tpd rather than 1000 tpd as was observed for the preceding eight cases. This necessitated the preparation of a new map of fuel requirements (Figure III-20), as were presented earlier in Figures III-4 and -5 for 1000 tpd systems. Each data point in Figure III-20 represents a value calculated by the procedure illustrated in Table III-3.

As with the preceding several cases, this system is an adaptation of a known burning mechanism but applied to a new fuel. In this case, the burning mechanism has been successfully used for the firing of solid fuels having a low content of volatiles, such as anthracite coal. The basic effect, illustrated in the schematic (Figure III-21), promotes a staged combustion of the fuel and favors relatively long residence times. Refuse, previously conditioned to a nominal 2-in. top size, is delivered to the burner by pneumatic means. Most of the air conveying the refuse to the furnace would be vented off just behind the fuel nozzle and be bypassed into the furnace through a separate nozzle. The refuse would thus tend to enter the furnace at low velocities. This type of burner, as used for anthracite coal, is illustrated in Figure III-22. Additional air is admitted to the furnace in a downward direction through the arch alongside the refuse burner and also through the side walls. As a further step to insure turbulence and prolonged residence time, air is also admitted through the hopper. Coal would also be fired in a downward direction from standard pulverized coal burners which would be situated between refuse burner cells.

The summary performance is shown in Table III-8. Because of the conditioning of the fuel, it is felt that the heat input from refuse could be as high as 80%.

Case 10 - Arch Furnace with Separate Superheater. This is a system which, in essence, is a combination of the original concept for Case 5 and that just discussed for Case 9. Refuse is burned in a furnace to generate superheated steam at 750°F, which then is further superheated to 1000°F in a separate coal-fired furnace, where reheating is also accomplished. This case thus exploits the advantages of the arch furnace (greater refuse throughput per unit) along with the advantages of operating with the separately fired superheater. As with Case 9, the success of this configuration hinges on whether a sufficient burnout of the refuse will occur. In order to insure constant ignition of the shredded refuse, coal would also be burned in the refuse-fired boiler, in an amount equal to 20% of the heat input.

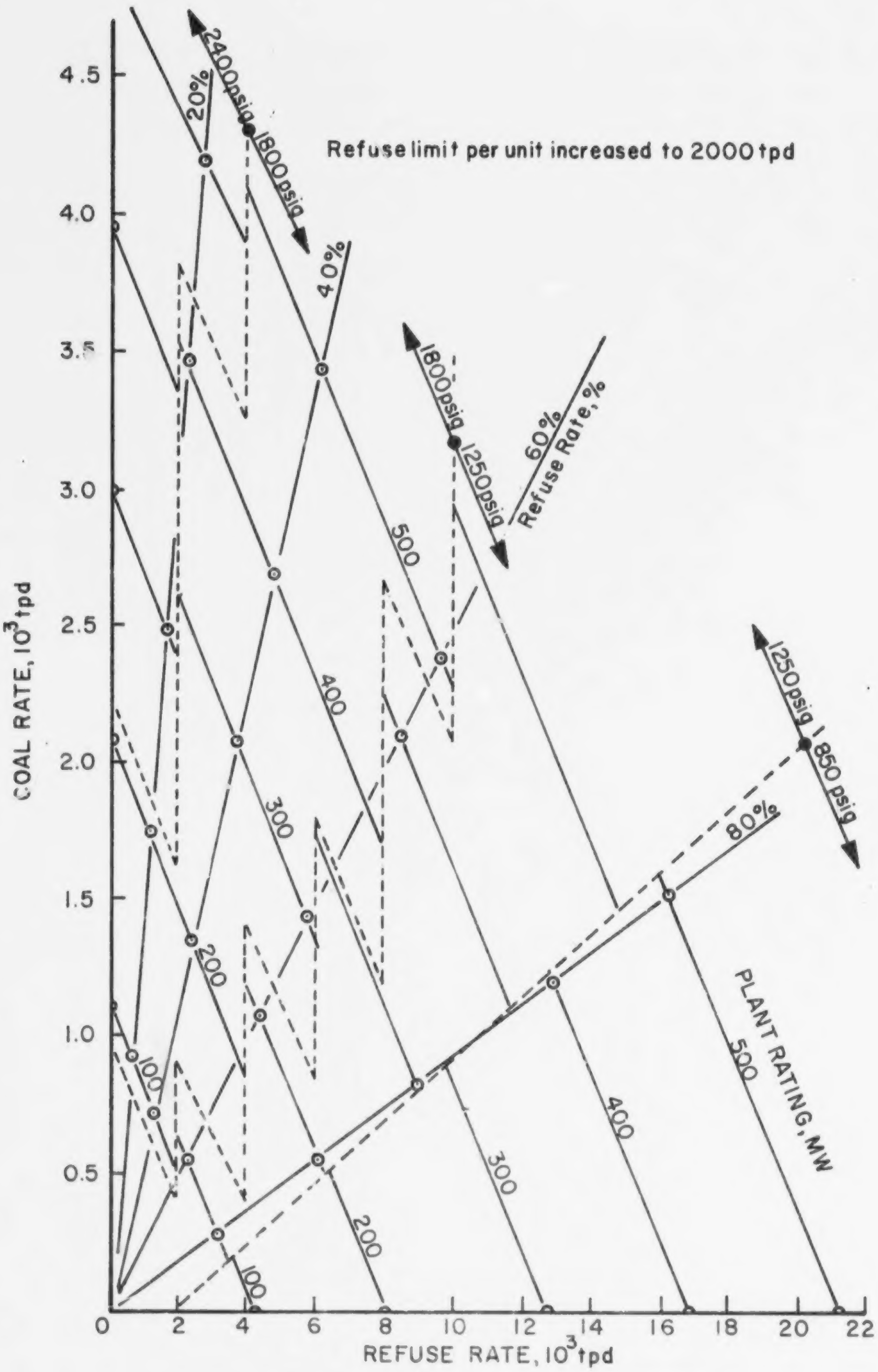


FIGURE III-20. ARCH FURNACE FUEL INPUT

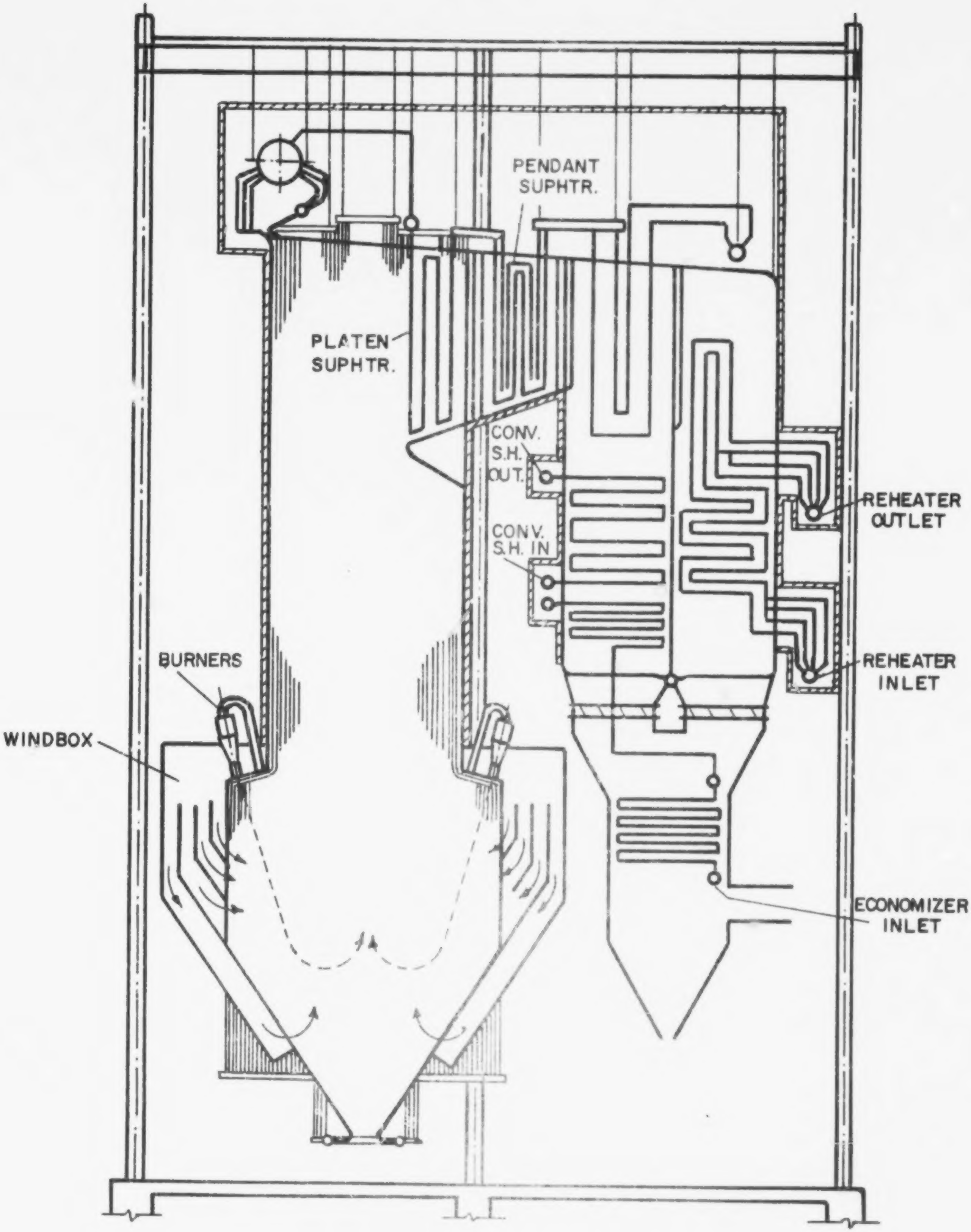

PENDANT
SUPHTR.
PLATEN
SUPHTR.
CONV.
S.H.
OUT.
REHEATER
OUTLET
CONV.
S.H. IN
BURNERS
REHEATER
INLET
WINDBOX
ECONOMIZER
INLET

FIGURE III-21. CASE 9 - ARCH FURNACE

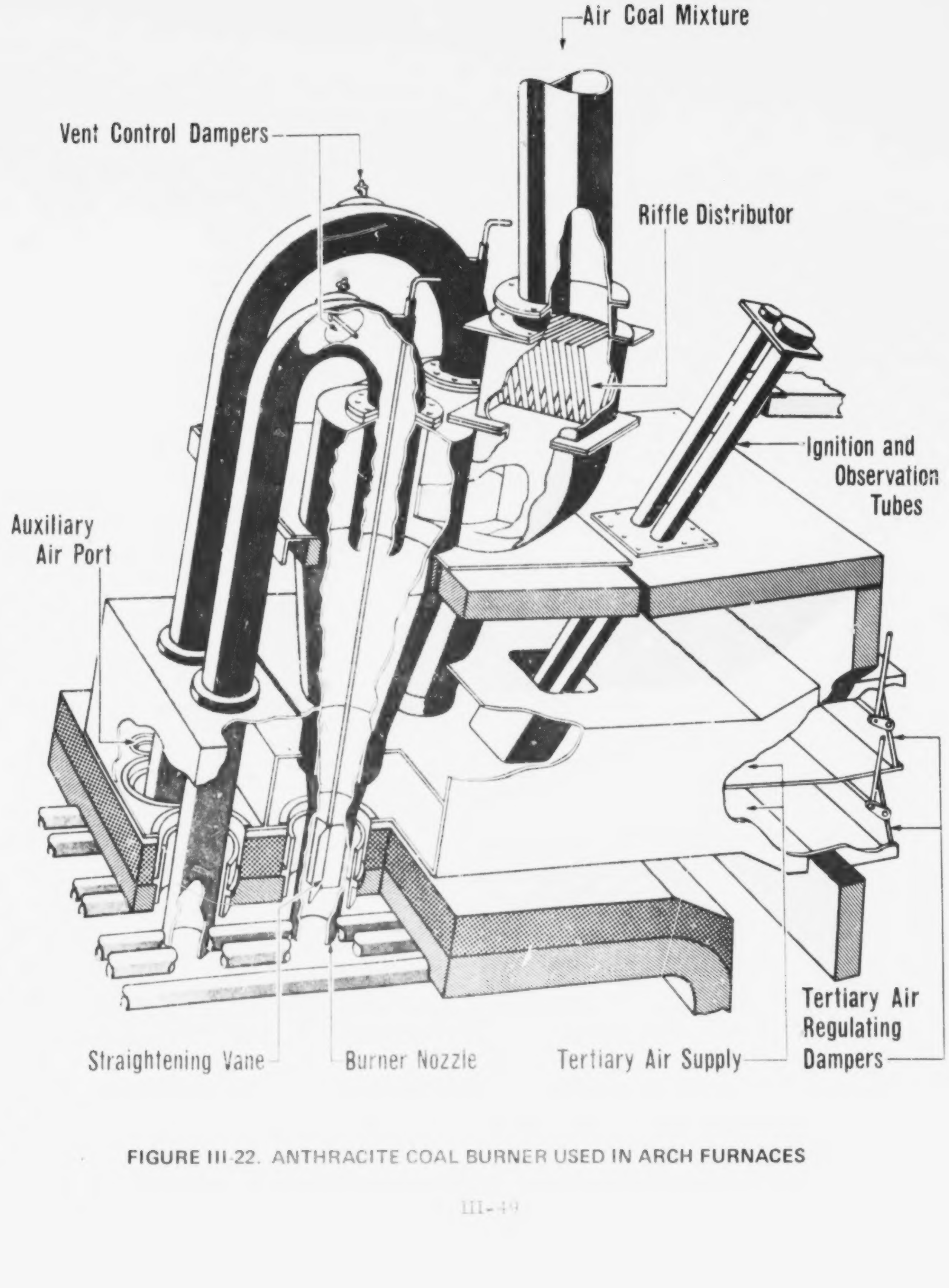

Air Coal Mixture
Vent Control Dampers
Riffle Distributor
Ignition and Observation Tubes
Auxiliary Air Port
Straightening Vane
Burner Nozzle
Tertiary Air Supply
Tertiary Air Regulating Dampers

FIGURE III-22. ANTHRACITE COAL BURNER USED IN ARCH FURNACES

TABLE III-8

CASE 9 - ARCH FURNACE: CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW								
	200					400			
Refuse Rate, %	0	20	40	60	80	0	20	40	60
Steam Pressure, psig	1800	1800	1800	1250	1250	2400	1800	1800	1250
Number of Turbines	1	1	1	3	3	1	2	2	5
Number of SG	1	1	2	3	4	1	2	3	5
SG Duty, 10^9 Btu/hr	1.75	1.75	0.88	0.68	0.51	3.32	1.75	1.17	0.79
Steam Flow, 10^3 lb/hr	1429	1429	715	610	470	2780	1429	950	715
Refuse Rate, tpd	0	1170	1210	1460	1520	0	1165	1610	1700
Coal Rate, tpd	2080	1727	674	360	141	3960	1728	897	420
Refuse Air, 10^3 lb/hr	0	467	483	583	607	0	465	643	679
Coal Air, 10^3 lb/hr	1992	1650	645	345	135	3790	1658	859	403
Total Air, 10^3 lb/hr	1992	2117	1128	928	742	3790	2123	1402	1082
Refuse FG, 10^3 lb/hr	0	548	566	685	712	0	545	744	797
Coal FG, 10^3 lb/hr	2180	1805	705	377	148	4140	1810	937	440
Total FG, 10^3 lb/hr	2180	2353	1271	1062	860	4140	2355	1681	1267
Net SG Efficiency, %	84.0	81.0	78.0	75.0	72.0	84.0	81.0	78.0	75.0
Net Plant Heat Rate, Btu/kw-hr	10,400	10,800	11,220	13,540	14,100	9,880	10,800	11,200	13,130

	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55

NOTE: Data shown are single SG's.

The basic steam generator configuration is shown in Figure III-23 and the summary performance is shown in Table III-9.

5. Design Data for Retrofit Systems

a. Background

In the previous analysis of (new construction) candidates, the steam conditions and unit sizes were established on the basis of what had been representative of most of the units ordered over the last few years. In considering units for modification for combined firing, the time span necessarily included units placed in service during the last twenty years, an era of rapid increase in steam conditions and unit size. Thus, certain deviations from the criteria established for new construction candidates became unavoidable.

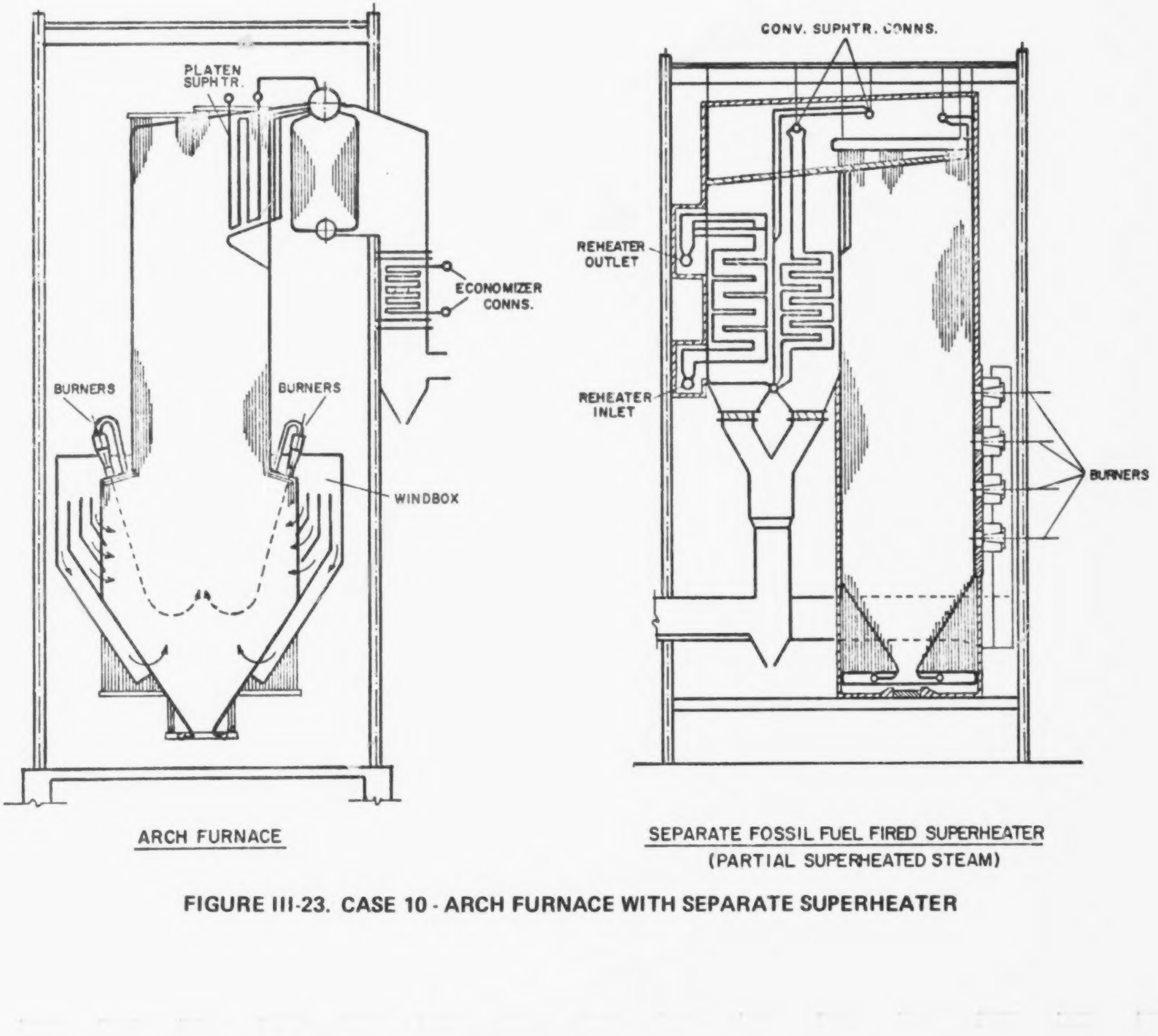
Steam generator and turbine efficiency had been fairly well established at their respective practical maximum levels during this era. Plant heat rates were lower, however, but basically because the auxiliary equipment used earlier was of considerable less efficiency than comparable modern equipment.

In considering candidates for modification, natural circulation units with balanced draft systems were chosen, as was done in the case of new units. This restriction did not result in the exclusion of a great number of retrofit candidates. Emphasis was placed on selecting units that would be representative of the many units placed in service over the last twenty years. Where possible, the criteria observed in the performance analysis of new units was also applied in considering the modification of existing units. This implied the imposition of an upper limit of unit sizes of 500 MW, the use of coal as the fossil fuel or a unit designed for coal-firing, the restriction of unit refuse rate to 1000 tpd or less (when a grate is used), and the maintenance of the flue gas exit-temperature at 450°F.

In considering plant modifications, it has been assumed that space would be available for the refuse handling equipment. Consideration was given to open areas and structural steel in close proximity to the steam generator. In general, updated building drawings were not available.

In applying the results of the analysis of (new construction) candidate steam generators, it became obvious that some of the new plant designs would not be applicable for the retrofit of existing plants.

Immediately excluded were the separately fired fossil fuel superheater designs (Cases 4, 5 and 10). The arch furnaces (Cases 9 and 10) were eliminated on the basis that the number of existing


PLATEN SUPHTR.
ECONOMIZER CONNS.
BURNERS
BURNERS
WINDBOX
CONV. SUPHTR. CONNS.
REHEATER OUTLET
REHEATER INLET
BURNERS

ARCH FURNACE

SEPARATE FOSSIL FUEL FIRED SUPERHEATER
(PARTIAL SUPERHEATED STEAM)

FIGURE III-23. CASE 10 - ARCH FURNACE WITH SEPARATE SUPERHEATER

TABLE III-9

CASE 10 - SEPARATE FOSSIL FUEL SUPERHEATER: CALCULATED SYSTEM CHARACTERISTICS

	Nameplate Rating, MW	
	200	400
Refuse Rate, %	59.8	56.4
Steam Pressure, psig	1800	1800
Number of Turbines	1	1
Number of SG (A/B)[1]	1/2	1/4
SG Duty, 10^9 Btu/hr	1.75	3.32
Steam Flow, 10^3 lb/hr	1430	2800
Refuse Rate/B, tpd	1880	1675
Coal Rate (A/B), tpd	591/349	1299/620
Refuse Air/B, 10^3 lb/hr	742	670
Coal Air (A/B), 10^3 lb/hr	567/334	1243/597
Total Air (A/B), 10^3 lb/hr	567/1076	1243/1267
Refuse FG/B, 10^3 lb/hr	882	785
Coal FG (A/B), 10^3 lb/hr	619/365	1359/648
Total FG (A/B), 10^3 lb/hr	619/1247	1359/1433
Net SG Efficiency, %	75.1	75.5
Net Plant Heat Rate, Btu/kw-hr	11,660	10,998
	Refuse	Coal
Excess Air, %	50	18
Air Ratio, lb Air/lb Fuel	4.80	11.50
Flue Gas Ratio, lb FG (wet)/lb Fuel	5.63	12.55

Note 1: A = Separate coal-fired superheater unit.
B = Refuse and coal (80/20) arch furnace unit.

units of this type is too small to warrant their inclusion. Also eliminated, for the same reason, were slagging furnaces (Case 8), many of which are pressurized. The separately fired economizer (Case 3) was initially considered a possible approach for retrofitting existing units. However, in designing the main fossil fuel steam generator, it was found that excluding the economizer from the conventional type steam generator with the requirement of full load operation with or without external feedwater heating would require a unique configuration for the main steam generator.

In summary, the designs considered for the modification of existing units are the separate or combined furnaces (Cases 1 and 2) and the firing variations thereof which involve suspension firing (Case 6) and spreader stoker firing (Case 7).

b. Selection of Existing Units

Four units were selected as being illustrative of existing systems. The characteristics of these four units, listed according to the appropriate modification plan (described later) for which each is considered, are given below.

CHARACTERISTICS OF EXISTING STEAM GENERATORS
SELECTED FOR MODIFICATION

Modification No.	Nameplate Rating MW	Steam Conditions psig/°F/°F	Steam Flow 10^3 lb/hr	Service Date
1	60	900/900/-	600	1949
2	150	2035/1050/1000	1,100	1959
3 & 4	44	1350/950/-	445	1957
5	300	2200/1010/1010	2,310	1961

Cross sectional drawings of these units are shown in Figures III-24 through -27. Full-load performance data for these units along with the design fuel are shown in Table III-10. Although the design fuel for Modification No. 3 is oil, the unit was also designed for possible future coal firing. Coal-burners were installed but not the coal-mills, bunkers, and other ancillary items.

In the new construction units considered in the previous analysis, the maximum permissible steam temperature developed from flue gases from separate or isolated refuse combustion was set at 750°F. Refuse is a fouling type fuel and this tendency increases with tube metal temperature. For the nonreheat units selected for modification,

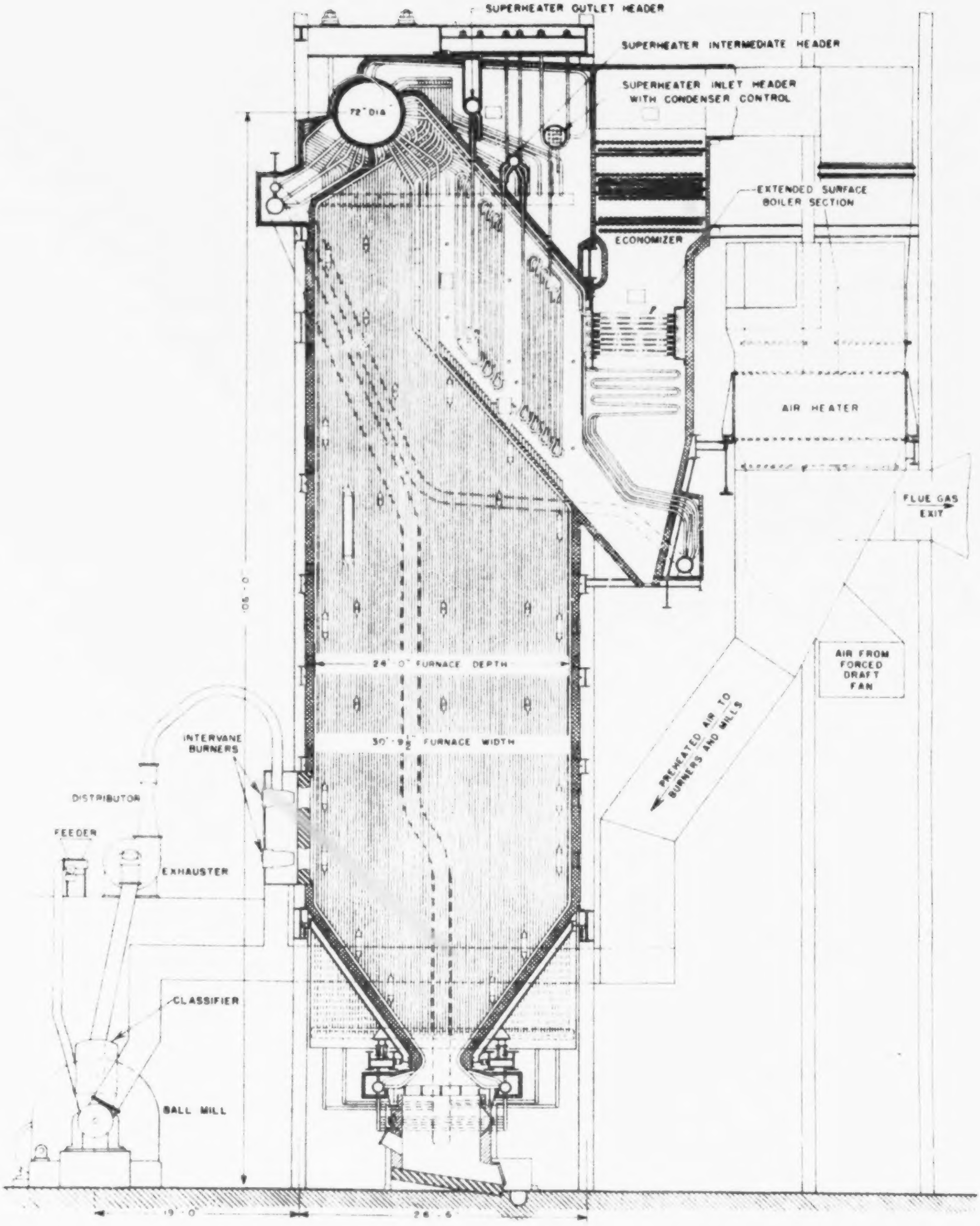

SUPERHEATER OUTLET HEADER
SUPERHEATER INTERMEDIATE HEADER
SUPERHEATER INLET HEADER WITH CONDENSER CONTROL
72" DIA
EXTENDED SURFACE BOILER SECTION
ECONOMIZER
AIR HEATER
FLUE GAS EXIT
AIR FROM FORCED DRAFT FAN
PREHEATED AIR TO BURNERS AND MILLS
106'-0"
24'-0" FURNACE DEPTH
30'-9½" FURNACE WIDTH
INTERVANE BURNERS
DISTRIBUTOR
FEEDER
EXHAUSTER
CLASSIFIER
BALL MILL
19'-0"
26'-6"

FIGURE III-24. EXISTING STEAM GENERATOR FOR MODIFICATION NO. 1

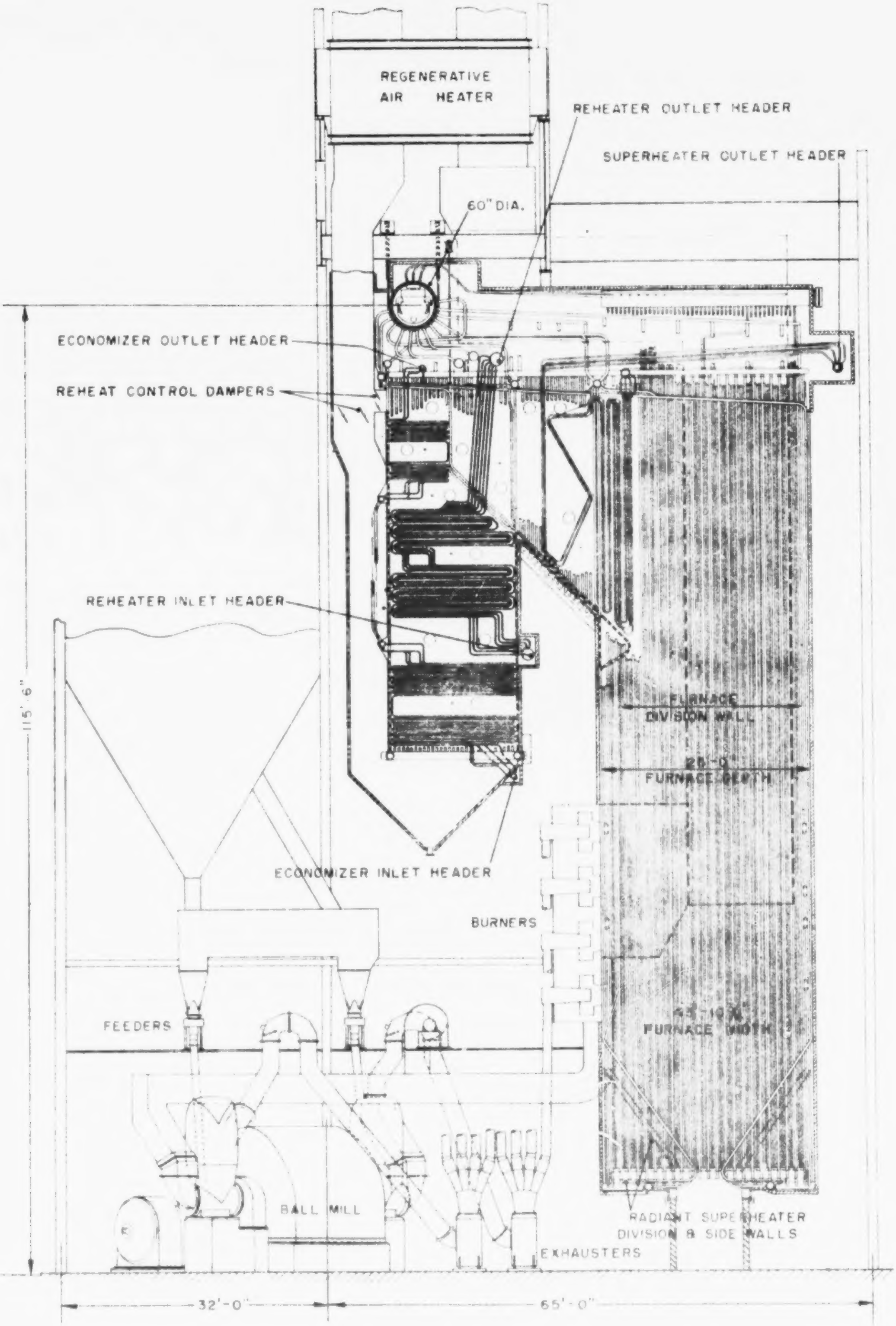

REGENERATIVE AIR HEATER
REHEATER OUTLET HEADER
SUPERHEATER OUTLET HEADER
60" DIA.
ECONOMIZER OUTLET HEADER
REHEAT CONTROL DAMPERS
REHEATER INLET HEADER
FURNACE DIVISION WALL
25'-0" FURNACE DEPTH
115'-6"
ECONOMIZER INLET HEADER
BURNERS
43'-10½" FURNACE WIDTH
FEEDERS
BALL MILL
RADIANT SUPERHEATER DIVISION & SIDE WALLS
EXHAUSTERS
32'-0"
65'-0"

FIGURE III-25. EXISTING STEAM GENERATOR FOR MODIFICATION NO. 2

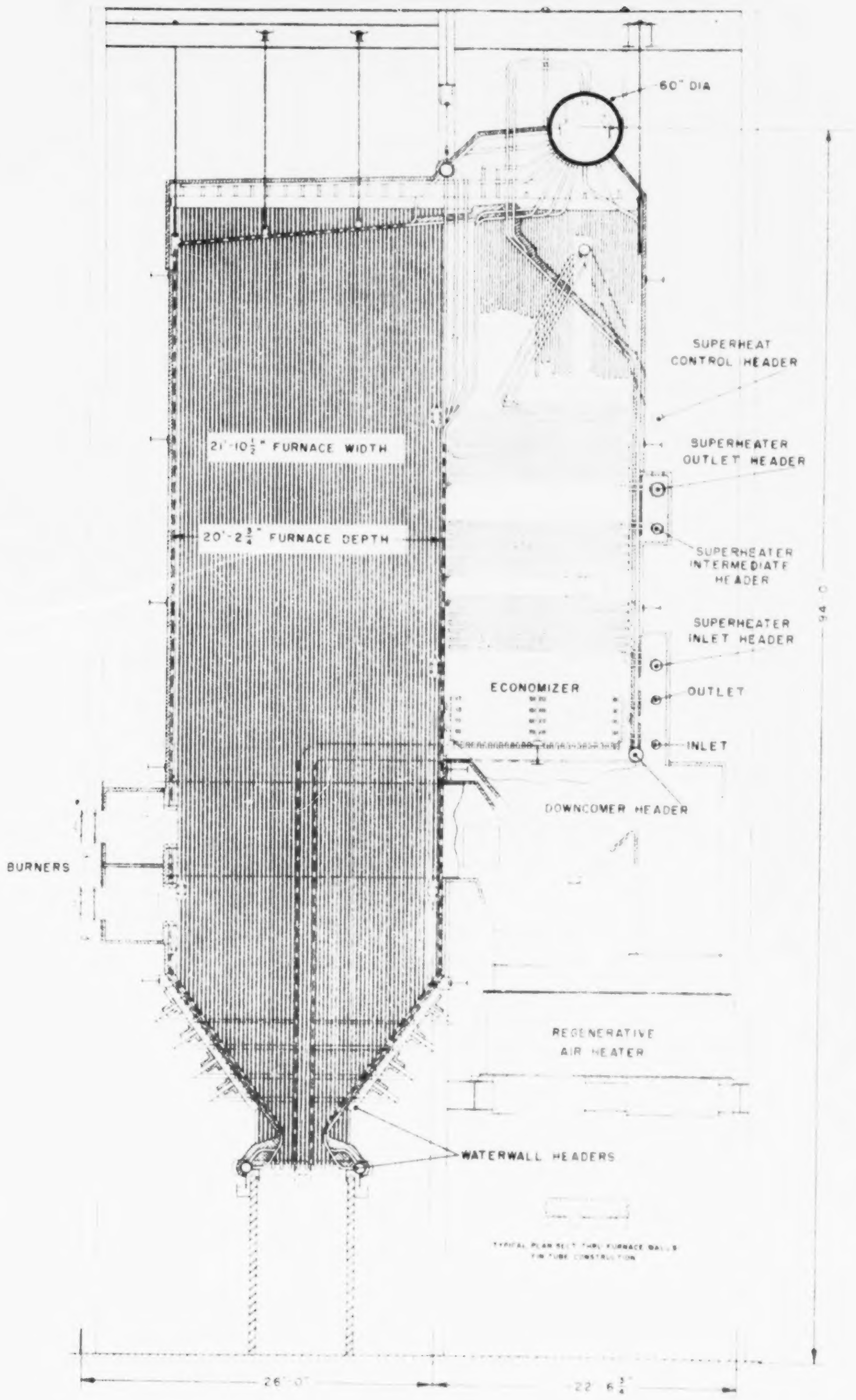

60" DIA
SUPERHEAT CONTROL HEADER
21'-10½" FURNACE WIDTH
SUPERHEATER OUTLET HEADER
20'-2¾" FURNACE DEPTH
SUPERHEATER INTERMEDIATE HEADER
94'-0"
SUPERHEATER INLET HEADER
ECONOMIZER
OUTLET
INLET
DOWNCOMER HEADER
BURNERS
REGENERATIVE AIR HEATER
WATERWALL HEADERS
TYPICAL PLAN SECT THRU FURNACE WALLS
FIN TUBE CONSTRUCTION
26'-0"
22'-6¾"

FIGURE III-26. EXISTING STEAM GENERATOR FOR MODIFICATIONS NO. 3 AND 4

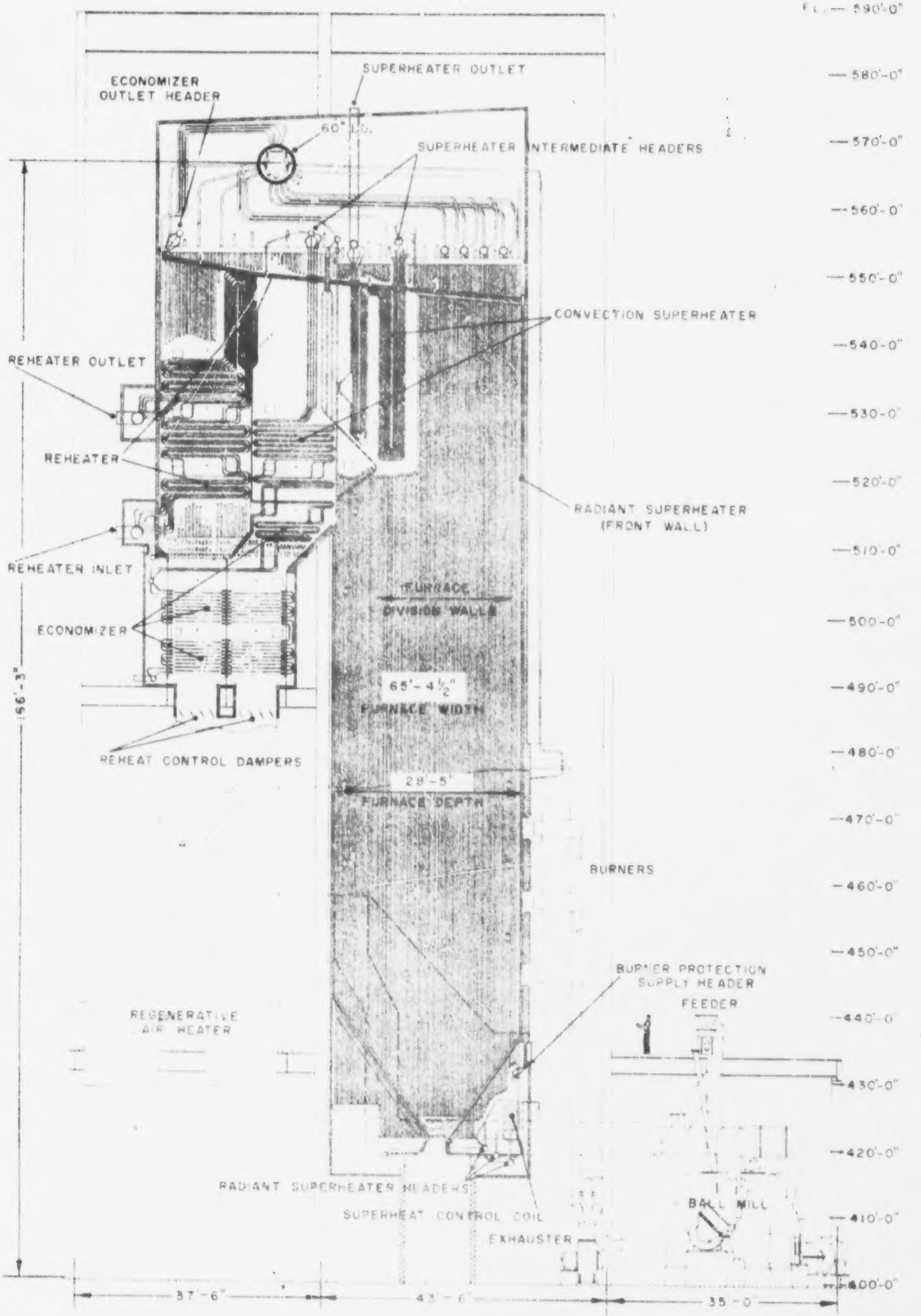

EL. — 590'-0"
— 580'-0"
— 570'-0"
— 560'-0"
— 550'-0"
— 540'-0"
— 530'-0"
— 520'-0"
— 510'-0"
— 500'-0"
— 490'-0"
— 480'-0"
— 470'-0"
— 460'-0"
— 450'-0"
— 440'-0"
— 430'-0"
— 420'-0"
— 410'-0"
— 400'-0"
SUPERHEATER OUTLET
ECONOMIZER OUTLET HEADER
60" I.D.
SUPERHEATER INTERMEDIATE HEADERS
CONVECTION SUPERHEATER
REHEATER OUTLET
REHEATER
RADIANT SUPERHEATER (FRONT WALL)
REHEATER INLET
FURNACE DIVISION WALLS
ECONOMIZER
65'-4 1/2"
FURNACE WIDTH
166'-3"
REHEAT CONTROL DAMPERS
28'-5"
FURNACE DEPTH
BURNERS
BURNER PROTECTION SUPPLY HEADER
FEEDER
REGENERATIVE AIR HEATER
RADIANT SUPERHEATER HEADERS
SUPERHEAT CONTROL COIL
BALL MILL
EXHAUSTER
37'-6"
43'-6"
35'-0"

FIGURE III-27. EXISTING STEAM GENERATOR FOR MODIFICATION NO. 5

TABLE III-10

SUMMARY OF PERFORMANCE DATA FOR SELECTED STEAM GENERATORS

Applicable Modification No.:	1	2	3 and 4	5
Steam output, 10^3 lb/hr	600	1,100	445	2,310
Superheater outlet temp., °F	-	-	950	1,010
Pressure, psig:				
Boiler drum	934	2,160	1,455	2,352
Superheater outlet	900	2,035	1,360	2,200
Reheat outlet temp., °F	-	1,003	-	1,010
Reheat outlet press., psig	-	419	-	566
Feedwater temp., °F	-	496	430	482
Exit air temp. at Air Heater, °F	555	638	456	613
Exit flue gas temp. at Air Heater, °F	301	290	340	308
Excess air, %:				
At boiler exit	23	-	10	20
At air heater exit	-	20	-	-
Flue gas (wet), 10^3 lb/hr:				
Economizer exit	746	-	-	-
Air heater exit	-	1,510	514	2,720
Fuel	Bituminous Coal	Bituminous Coal	Fuel Oil	Bituminous Coal
Fuel rate, 10^3 lb/hr	54.5	123.5	29.5	267
Ultimate Analysis,* wt-%				
Ash	8.55	13.00		10.5
Sulfur	1.90	3.49	2.5	3.5
Hydrogen	4.26	4.32	10.18	4.7
Carbon	75.00	63.93	86.69	61.4
Moisture	5.00	7.00		11.0
Nitrogen	1.13	1.30	0.14	1.2
Oxygen	4.10	6.96	0.49	7.7
Fuel value, as fired (HHV), Btu/lb	13,300	11,600	18,400	10,280
Plant heat rate, Btu/kw-hr	12,090	9,560	12,340	9,140

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*Assumed for design purposes.

however, the steam temperatures are 900 and 950°F. As will be shown later, these units were modified so that the refuse fuel bed would be positioned below the fossil fuel flame envelope. The flue gas and fly ash from the former, in passing through the latter, would thus undergo more complete combustion. This effect was demonstrated at Munich North, Unit No. 2. Also, the superheater spacings in these units are wider than is found in present-day units. This, too, should serve to reduce tube wastage to an acceptable level in these units.

The reheat units have superheat temperatures slightly above 1000°F and are more susceptible to fouling than the nonreheat units. However, in modifying these units steps were again taken to minimize fouling.

Many units built over the last twenty years have radiant superheaters that are located in the furnace where tube metal temperatures can approach 1000°F. The steam generators shown in Figures III-24 and -25 are illustrative of this type of construction. Therefore, these units should not be fired with refuse on a grate, if any radiant superheater surface is exposed. As shown later, these units have been modified to minimize potential tube wastage.

c. Modification Requirements

The procedures involved in planning the modification of each of the units were somewhat similar. Where grates are to be installed, it is necessary to cut and remove the existing furnace hopper tubes. New sections of tubing that are of the proper shape for a refuse combustion area must be welded to the existing furnace tubes. New lower water-wall headers are required and the new sections of tubing must be insulated. Stokers and charging chutes must be installed and access provided for service.

A combustion-air system for firing refuse is required. This system includes fans, ducts, and dampers. It was initially thought that the existing fans might also serve to supply the refuse combustion-air, but it was found that this would not be practical. The amount of combustion air that could be diverted from the coal firing system because of the reduced coal-rate would not be quite enough to provide even the stoichiometric refuse combustion air; furthermore, many operational problems would be caused by the dual use of the fans. Static pressure heads on the existing fans may not be correct for the refuse air system. Also it would be difficult to build an air distribution system that would accurately distribute air between the two dissimilar firing systems. Therefore, in most of the modifications, additional fans are specified that will provide the full refuse air requirement.

It is anticipated that additional soot blowers will also be required in the convection passes, and that some air heater elements will have to be removed from existing regenerative air heaters. In some cases the secondary support steel has had to be changed.

The amount of refuse that each modified unit can consume is primarily determined by the size grate that can be accommodated. This presumes that in the furnace enclosure, usually of a rectangular plan area where two opposite walls bend in to form a hopper, only two of the walls would need to be modified. It soon became apparent, however, that the appropriate approach was to modify the hopper walls and simply extend the length of the other walls. This essentially implies that the maximum refuse-rate would be dependent upon the existing furnace width. All of the units shown with reciprocating grates can accommodate other types of agitating grates with few if any design changes. The refuse rates were calculated on the basis of sixty pounds of refuse per square foot of net grate area per hour. The heat input from refuse is again based on a higher heating value of 4,460 Btu/lb and 69% steam generator efficiency when firing refuse exclusively.

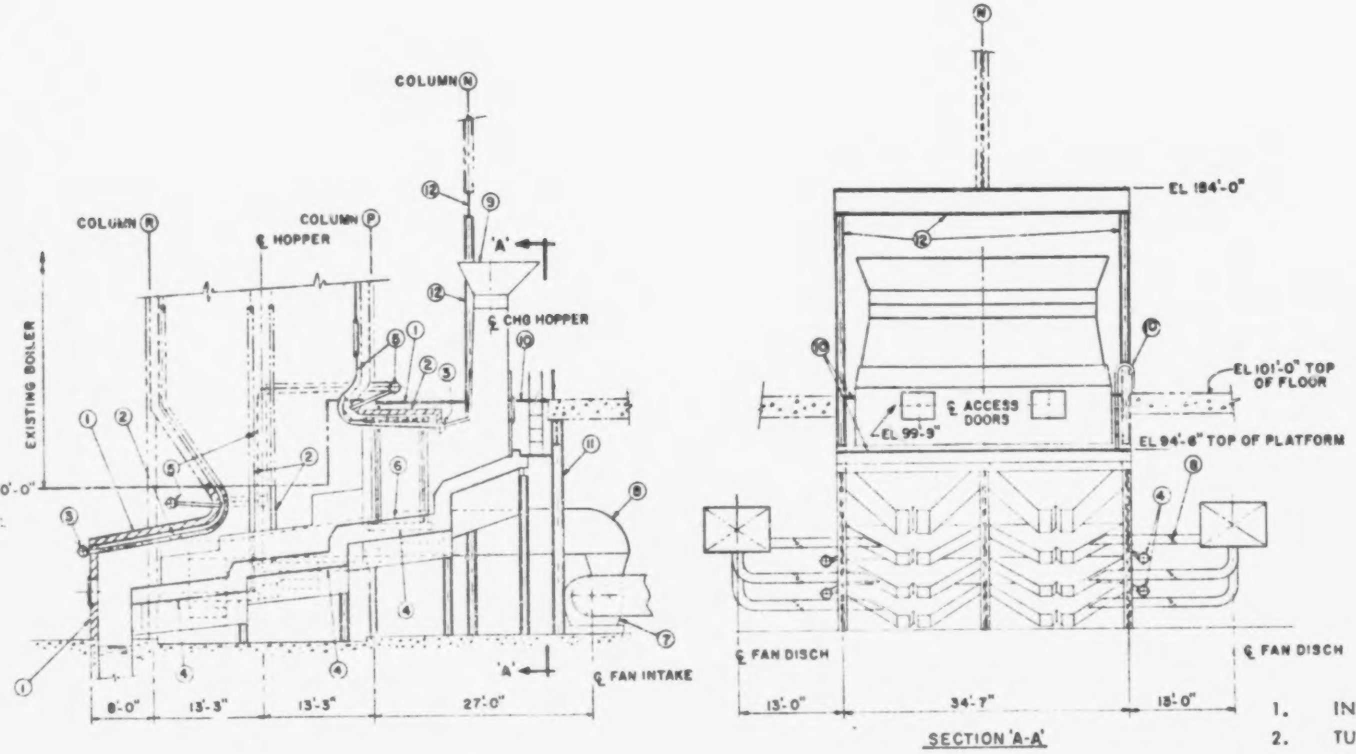
d. Candidate Retrofit Systems

Modification No. 1. The unit modified (Figure III-24) is typical of pulverized coal or oil steam generators built in the late 1940's. One of two duplicate units at an eastern power plant, it was designed for an output of 600,000 lb/hr superheated steam at 900 psig and 900°F. In the 1940's the present practices of using reheaters and monowall furnace construction were not yet developed. Units built at this time are now largely on standby duty and could probably be made available for modification.

In order to adapt this unit for refuse firing, the lower area of the furnace was modified to assume the shape required for refuse combustion (Figure III-28). This requires bent tube sections for the rear and front water walls, and extension of the side water walls. A new section of water wall is placed at the first grate section. Two underfire air fans and the underfire air ducts are provided. Each plenum chamber air supply is separately controlled by dampers. Ducts and nozzles are provided for the overfire air system, which is also supplied by the two fans.

This modified unit will be capable of firing 951 tpd of refuse, which is approximately 43% of the required heat input. There should be no problem in running at full load using coal as the only fuel.

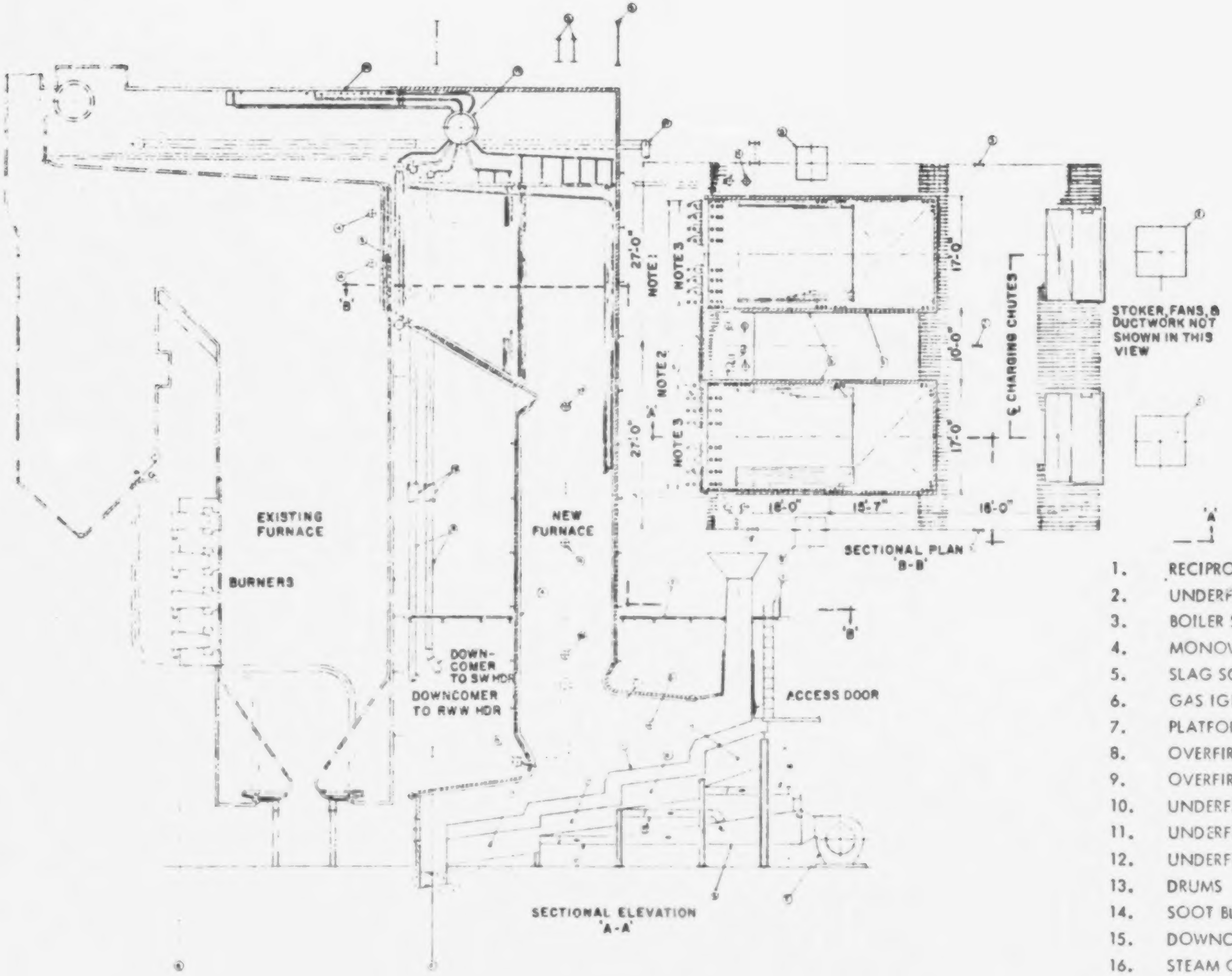
Modification No. 2. This modification is an example of adapting a steam generator to combined firing utilizing separate furnaces for refuse and fossil fuels. It corresponds to Case 1 in the new construction designs. The unit chosen for modification (Figure III-25) generates steam at 2035 psig and 1053°F. The main steam generation rate is 1,100,000 lb/hr using a reheat cycle. This steam generator, one of seven identical units, was installed in a Southern State in the late 1950's. The modification is shown in Figure III-29. Two separate refuse boilers generating saturated steam would be required.


COLUMN Ⓝ
COLUMN Ⓡ
COLUMN Ⓟ
℄ HOPPER
'A'
℄ CHG HOPPER
EXISTING BOILER
EL 90'-0"
'A'
℄ FAN INTAKE
8'-0"
13'-3"
13'-3"
27'-0"
Ⓝ
EL 104'-0"
EL 101'-0" TOP OF FLOOR
℄ ACCESS DOORS
EL 99'-9"
EL 94'-6" TOP OF PLATFORM
℄ FAN DISCH
℄ FAN DISCH
13'-0"
34'-7"
13'-0"
SECTION 'A-A'
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫

LEGEND

1. INSULATION
2. TUBING
3. FRONT AND REAR WALL HEADERS
4. SIDE WALL HEADERS
5. OVERFIRE AIR SYSTEM
6. RECIPROCATING GRATE
7. UNDERFIRE AIR FANS
8. UNDERFIRE AIR DUCT WORK AND DAMPERS
9. REFUSE CHARGING HOPPER
10. PLATFORMS
11. FLOOR SUPPORT STEEL
12. BOILER SUPPORT STEEL

FIGURE III-28. BOILER MODIFICATION NO. 1


EXISTING FURNACE
BURNERS
NEW FURNACE
DOWN-COMER TO SW HDR
DOWNCOMER TO RWW HDR
ACCESS DOOR
SECTIONAL ELEVATION 'A-A'
SECTIONAL PLAN 'B-B'
'A'
'B'
NOTE 1
NOTE 2
NOTE 3
NOTE 3
27'-0"
27'-0"
17'-0"
10'-0"
17'-0"
16'-0"
15'-7"
16'-0"
℄ CHARGING CHUTES
STOKER, FANS, & DUCTWORK NOT SHOWN IN THIS VIEW

LEGEND

1. RECIPROCATING GRATE
2. UNDERFIRE AIR FANS
3. BOILER SUPPORT STEEL
4. MONOWALL TUBING
5. SLAG SCREEN MADE FROM EXISTING FURNACE WALL
6. GAS IGNITORS
7. PLATFORMS
8. OVERFIRE AIR DUCTS, DAMPERS AND NOZZLES
9. OVERFIRE AIR FANS
10. UNDERFIRE AIR FEED DUCTS
11. UNDERFIRE AIR PLENUM CHAMBER
12. UNDERFIRE AIR FEED DUCTS
13. DRUMS
14. SOOT BLOWERS
15. DOWNCOMER PIPING
16. STEAM OUTLET PIPING
17. INSULATION FOR DOWNCOMERS
18. FURNACE WALL SOOT BLOWERS
19. RADIANT SUPERHEATER INLET HEADER

FIGURE III-29. BOILER MODIFICATION NO. 2

This unit was chosen because of the feature of rear-wall firing. Although this is the desired configuration in coupling to another furnace, it does seriously narrow the number of existing steam generators that can be retrofitted.

The addition of two refuse furnaces would not be necessary in every case. It was done this way in the present situation because the existing unit was too wide to accept a grate of the same width, and because there was a boiler support column at the center of the existing front wall. If a unit were modified by adding a single refuse furnace, however, the cost savings would not be great.

The resulting modified unit would be capable of incinerating 1,000 tpd of refuse. This would account for approximately 24% of the heat input.

Initially, the separate furnace scheme appeared to be quite feasible, but as the designing progressed, the problems and disadvantages increased drastically. Overcoming each technical problem that developed necessitated the addition of more hardware. The resulting cost of this modification proved to be very high, which, coupled with the dubious technical benefits of this type of unit, led to the conclusion that the scheme might be impractical for existing steam generators.

Modifications No. 3 and 4. The steam generator used for Modifications No. 3 and 4 (Figure III-26) was built for a New England power company in the mid-1950's as one of two identical units. It has no reheat cycle and there is no radiant superheat surface in the furnace. The furnace walls are of monowall construction. This unit was designed for 445,000 lb/hr steam at 1,350 psig and 950°F. It was originally built for oil firing with provision for future coal firing.

Modification No. 3, as shown in Figure III-30, involves the retrofit of the unit with a spreader stoker refuse-firing system. The furnace hopper has had to be changed in much the same manner as would be necessary for installing a reciprocating grate system. The hopper was replaced by straight front and rear water walls, and extended side walls. New lower water wall headers have been provided. Six air-swept spouts feed shredded refuse, sized to pass through a 4-in. grid, into the furnace. A travelling grate has been specified to insure the combustion of refuse that does not completely burn while in suspension.

This arrangement would be more attractive if the fossil fuel burners were situated in the rear wall. The layout of the convection passes, however, did not permit the relocation of the burners as part of the design modification. A few design compromises were made, therefore, in order to provide access to the coal burners. On the whole, however, there were few problems encountered with this modification. Fans were provided for the air-swept spouts and the overfire air, although it was assumed that the existing fans could supply the underfire grate-air.

LEGEND

1. AIR-SWEPT DISTRIBUTOR SPOUTS
2. TRAVELING GRATE
3. REFUSE FEED-CHUTE
4. OVERFIRE AIR DUCT
5. OVERFIRE AIR FAN
6. ASH HOPPER
7. FURNACE REAR TUBE WALL
8. FURNACE SIDE TUBE WALL
9. UPPER REAR WALL OVERFIRE AIR-NOZZLES (16), 1-1/4" ɸ SCHED 80
10. LOWER REAR WALL OVERFIRE AIR NOZZLES (16), 1-1/8" ɸ STAINLESS
11. UPPER FRONT WALL OVERFIRE AIR NOZZLES (20), 1" x 2" OUTS.
12. LOWER FRONT WALL OVERFIRE AIR NOZZLES (16), 1" ɸ SCHED 40
13. LOWER WATER WALL HEADER
14. FURNACE INSULATION
15. VIBRATING FEEDER

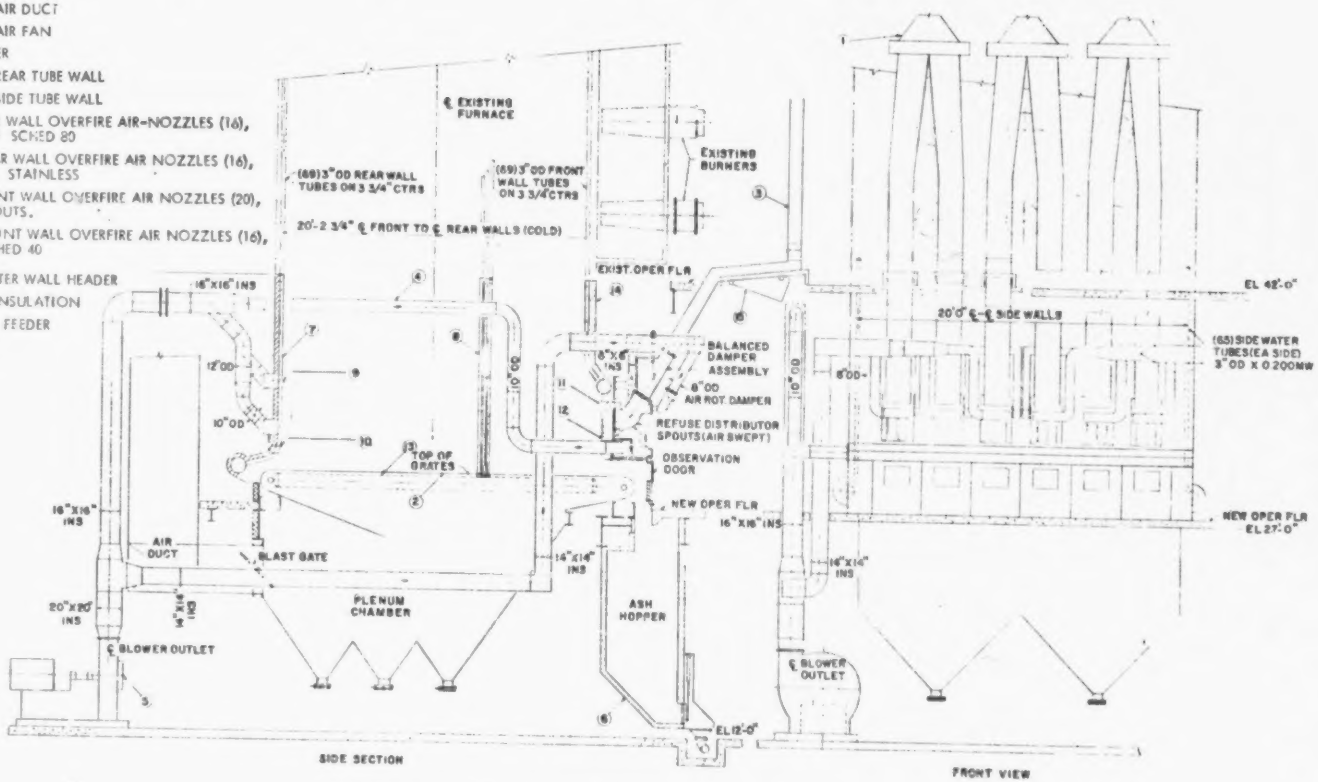

℄ EXISTING FURNACE
(69) 3" OD REAR WALL TUBES ON 3 3/4" CTRS
(69) 3" OD FRONT WALL TUBES ON 3 3/4" CTRS
EXISTING BURNERS
20'-2 3/4" ℄ FRONT TO ℄ REAR WALLS (COLD)
EXIST. OPER FLR
16"X16" INS
12" OD
10" OD
10" OD
TOP OF GRATES
BALANCED DAMPER ASSEMBLY
8"X8" INS
8" OD AIR ROT. DAMPER
REFUSE DISTRIBUTOR SPOUTS (AIR SWEPT)
OBSERVATION DOOR
NEW OPER FLR
16"X16" INS
16"X16" INS
AIR DUCT
BLAST GATE
14"X14" INS
PLENUM CHAMBER
ASH HOPPER
20"X20" INS
14"X14" INS
℄ BLOWER OUTLET
EL 12'-0"
SIDE SECTION
EL 42'-0"
20'0" ℄-℄ SIDE WALLS
(65) SIDE WATER TUBES (EA SIDE) 3" OD X 0.200MW
8" OD
10" OD
NEW OPER FLR EL 27'-0"
14"X14" INS
℄ BLOWER OUTLET
FRONT VIEW
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

FIGURE III-30. BOILER MODIFICATION NO. 3

It is estimated that this modified unit will be capable of consuming 846 tpd of refuse. This refuse-rate will supply about 51% of the heat input. There is some uncertainty concerning the refuse-rate, because this type of firing has not been used for refuse in the past. Considering the related experience with stoker-spreaders in firing other waste fuels, such as bark and bagasse, the specified rate can probably be regarded as conservative.

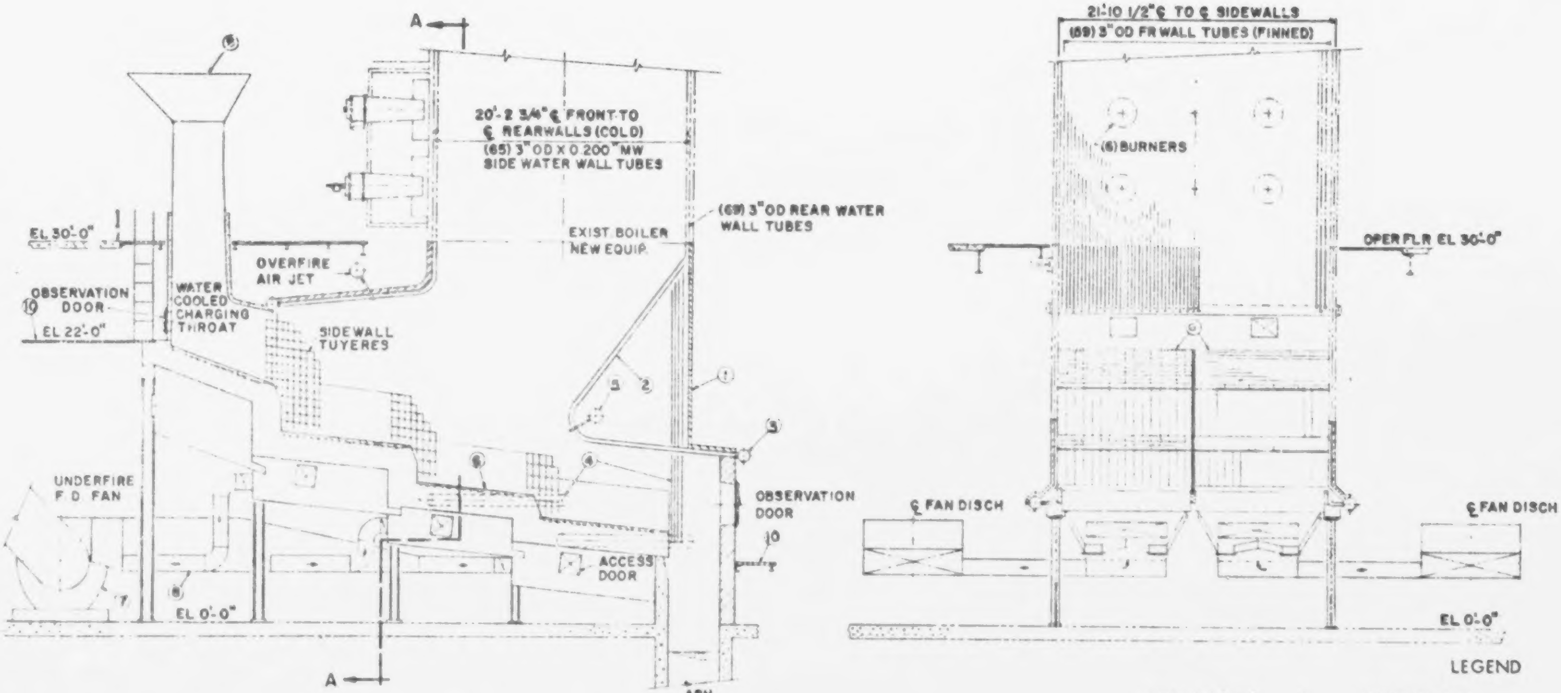
Modification No. 4, as shown in Figure III-31, involves the same existing steam generator (Figure III-26) as was considered for Modification No. 3. In this case, however, the unit has been modified for grate firing. This modification also requires certain design compromises in order to provide access to the existing fuel burners. The shape of the lower furnace has been made such that the clearance between the refuse charging chute and the burners would be sufficient to remove the burners. This modified unit should burn 679 tpd of refuse, which would be 42% of the heat input.

On a superficial basis, this modification would appear to be identical with Modification No. 1. The construction features of the boilers are, however, quite different and reflect the retrofit problems that would be encountered between older or more recent generation units. For example, Modification No. 1 involves a boiler fitted with tangent tube walls in which the furnace seals are situated in the refractory behind the tubes. This older boiler also offers a situation wherein the refuse introduction equipment, particularly the chute, can be installed with minimum difficulty arising from existing structures. The boiler selected for Modifications No. 3 and 4, on the other hand, is of monowall construction, which is more amenable to structural rearrangements, but presents the problem of limited placement area for refuse-chute installation.

Another aspect favoring the inclusion of Modification No. 4 is that it permits direct cost comparison of reciprocating grate and stoker-spreader retrofit systems installed in the same boiler.

Modification No. 5. The unit selected for the present modification (Figure III-27) is owned by a mid-west utility company. It was one of several units considered for possible modification to refuse-firing in a recently completed study (Ref. 41) dealing with the present subject. This unit was designed to fire bituminous coal. It generates 2,310,000 lb/hr of superheated steam at 2,200 psig and 1010°F. This unit also has a reheat cycle that supplies 1,790,000 lb/hr of steam at 568 psig. Figures III-32 and -33 show the modifications required for refuse firing.

Along with the width of the unit, the furnace is essentially divided into three chambers by the two full division walls. Refuse will be injected into each of these sections through refuse nozzles placed above the top burner row. There will be two nozzles per section, one on the front wall and one on the rear wall.



A
9
20'-2 3/4" ℄ FRONT TO
℄ REARWALLS (COLD)
(65) 3" OD X 0.200" MW
SIDE WATER WALL TUBES
(69) 3" OD REAR WATER
WALL TUBES
EXIST BOILER
NEW EQUIP
EL 30'-0"
OVERFIRE
AIR JET
OBSERVATION
10 DOOR
WATER
COOLED
CHARGING
THROAT
EL 22'-0"
SIDEWALL
TUYERES
5
2
1
3
6
4
UNDERFIRE
F D FAN
7
8
EL 0'-0"
OBSERVATION
DOOR
10
ACCESS
DOOR
A
ASH
HOPPER
21'-10 1/2" ℄ TO ℄ SIDEWALLS
(69) 3" OD FR WALL TUBES (FINNED)
(6) BURNERS
OPER FLR EL 30'-0"
℄ FAN DISCH
℄ FAN DISCH
EL 0'-0"

SECTIONAL ELEVATION

SECTION 'A-A'

LEGEND

1. INSULATION
2. TUBING
3. REAR AND FRONT WATER WALL HEADERS
4. SIDE WATER WALL HEADERS
5. OVERFIRE AIR SYSTEM
6. RECIPROCATING GRATE
7. UNDERFIRE FORCED DRAFT FAN
8. UNDERFIRE AIRDUCTS
9. REFUSE CHARGING CHUTE
10. PLATFORM

FIGURE III-31. BOILER MODIFICATION NO. 4

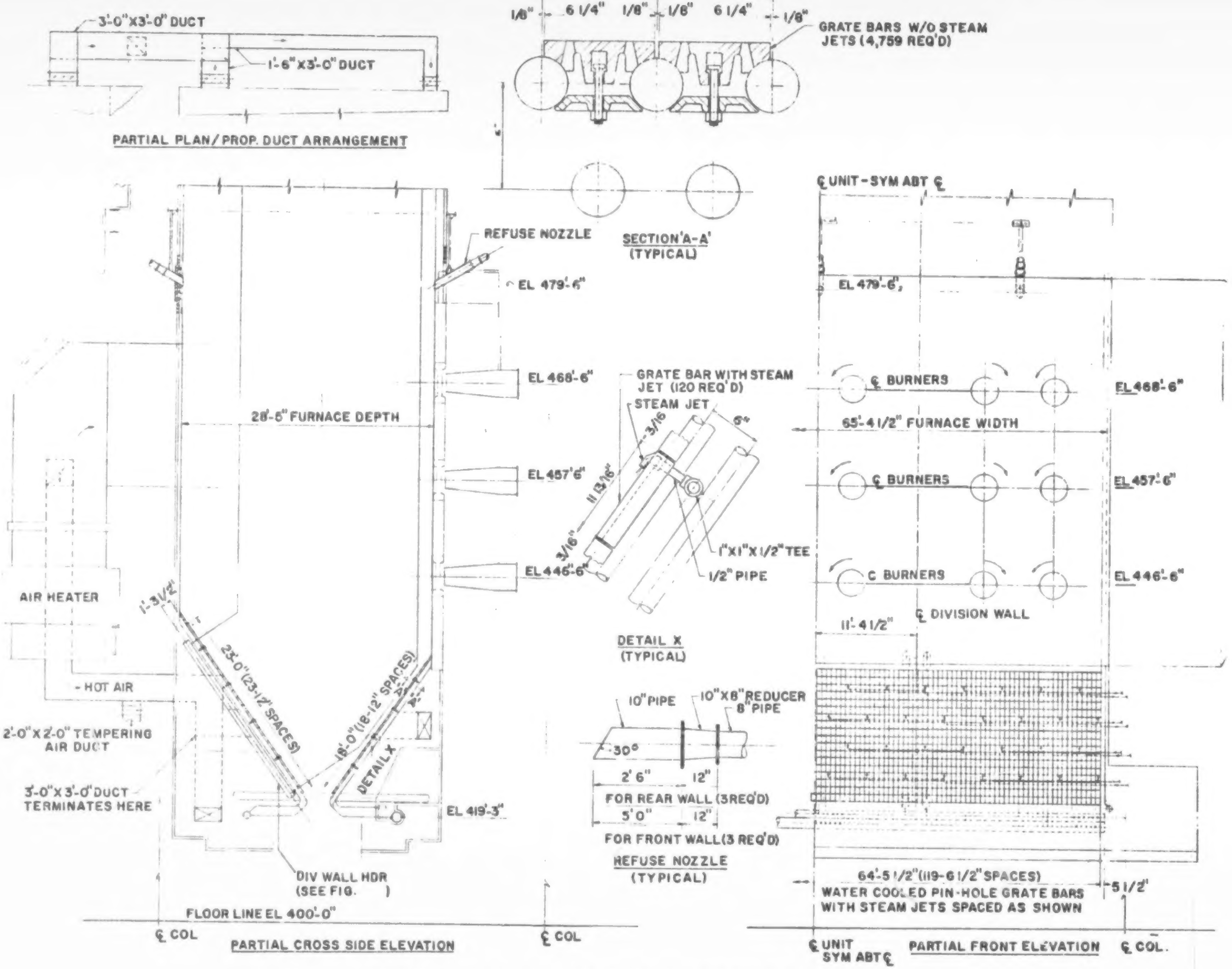

3'-0"X3'-0" DUCT
1'-6"X3'-0" DUCT
PARTIAL PLAN/ PROP. DUCT ARRANGEMENT
6 1/2"
6 1/4"
1/8"
6 1/2"
6 1/4"
1/8"
1/8"
1/8"
GRATE BARS W/O STEAM JETS (4,759 REQ'D)
SECTION 'A-A' (TYPICAL)
REFUSE NOZZLE
EL 479'-6"
EL 468'-6"
EL 457'6"
EL 446'-6"
28'-5" FURNACE DEPTH
AIR HEATER
1'-3 1/2"
23'-0" (23-12" SPACES)
18'-0" (18-12" SPACES)
DETAIL X
HOT AIR
2'-0"X2'-0" TEMPERING AIR DUCT
3'-0"X3'-0" DUCT TERMINATES HERE
EL 419'-3"
DIV WALL HDR (SEE FIG.)
FLOOR LINE EL 400'-0"
℄ COL
PARTIAL CROSS SIDE ELEVATION
℄ COL
GRATE BAR WITH STEAM JET (120 REQ'D)
STEAM JET
3/16
6"
11 13/16"
3/16"
1"X1"X1/2" TEE
1/2" PIPE
DETAIL X (TYPICAL)
10" PIPE
10"X8" REDUCER
8" PIPE
30°
2' 6"
12"
FOR REAR WALL (3 REQ'D)
5' 0"
12"
FOR FRONT WALL (3 REQ'D)
REFUSE NOZZLE (TYPICAL)
℄ UNIT-SYM ABT ℄
EL 479'-6"
℄ BURNERS
65'-4 1/2" FURNACE WIDTH
℄ BURNERS
C BURNERS
EL 468'-6"
EL 457'-6"
EL 446'-6"
℄ DIVISION WALL
11'-4 1/2"
64'-5 1/2" (119-6 1/2" SPACES)
WATER COOLED PIN-HOLE GRATE BARS WITH STEAM JETS SPACED AS SHOWN
5 1/2"
℄ UNIT SYM ABT ℄
PARTIAL FRONT ELEVATION
℄ COL.

FIGURE III-32. BOILER MODIFICATION NO. 5

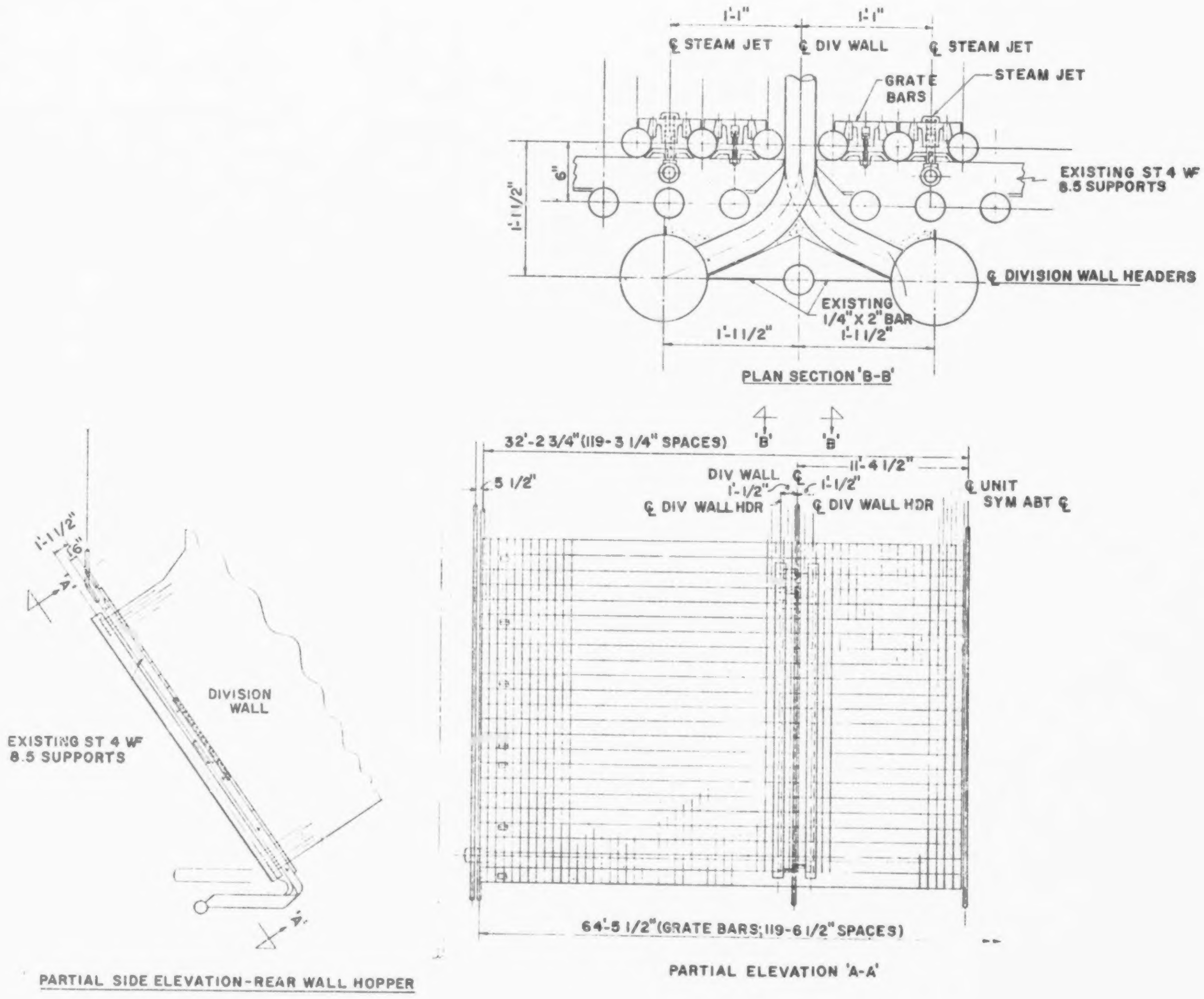

1'-1"
1'-1"
℄ STEAM JET
℄ DIV WALL
℄ STEAM JET
GRATE BARS
STEAM JET
6"
1'-11/2"
EXISTING ST 4 WF 8.5 SUPPORTS
℄ DIVISION WALL HEADERS
EXISTING 1/4" X 2" BAR 1'-11/2"
1'-11/2"
PLAN SECTION 'B-B'
'B'
'B'
32'-2 3/4" (119-3 1/4" SPACES)
11'-4 1/2"
5 1/2"
DIV WALL ℄
1'-1/2"
1'-1/2"
℄ DIV WALL HDR
℄ DIV WALL HDR
℄ UNIT SYM ABT ℄
64'-5 1/2" (GRATE BARS; 119-6 1/2" SPACES)
PARTIAL ELEVATION 'A-A'
1'-11/2"
6"
'A'
'A'
DIVISION WALL
EXISTING ST 4 WF 8.5 SUPPORTS
PARTIAL SIDE ELEVATION-REAR WALL HOPPER

FIGURE III-33. BOILER MODIFICATION NO. 5 - DETAIL OF DIVISION WALL/HOPPER INTERSECTION

In the event that there is insufficient burn-out of refuse while it is in suspension, the furnace hopper would have been modified to provide a surface for additional burning. The hopper tubes would be replaced by a slightly altered tube arrangement so that water-cooled grate bars could be attached. The header-box under the furnace hopper would be converted into a plenum chamber for the underfire grate air. It has also been considered necessary to insulate some of the headers in the header-box, and to run air ducts into the header-box.

The coal intervane-burner rotations are shown in Figure III-32. It was felt that the downward flow of air between the two coal burners in each section of the furnace would tend to give the refuse an extremely turbulent burning path. Steam jets would be placed at certain locations on the hopper. These would be operated periodically to remove ash deposits from the grate bars. It should be pointed out that the angle of the stationary grate is rather critical. The angle of the existing hopper floor is close to the values usually recommended.

It was felt that the existing forced draft fans could be used for the type of combined firing considered in this modification. A tempering air duct system would be included to maintain the underfire air temperature below 350°F. The required refuse combustion air that is not admitted through the grate would be taken from the existing windbox. It has been assumed that this air would be admitted through the coal burners. If this proves to be inadequate, additional openings would be installed in the front wall so that secondary air from the windbox could flow directly into the furnace.

Most of the cost of this modification would be incurred in the modification of the hopper area and the duct work to transport underfire air to this area. If it were determined that burnout would be sufficient without the installation of grate bars and underfire air system, the total cost would be drastically reduced.

6. Air Pollution Control (APC) Equipment

a. Overview

On the present program, the abatement of SO_2 emissions is of course a key objective. The approach taken, however, is based on the scheme of supplanting a portion of the high sulfur fuel used in power boilers with one of lower sulfur content. That the replacement fuel also happens to constitute a major waste management problem considerably amplifies the interest that its combustion characteristics would otherwise merit.

In this context, therefore, the specification of air cleaning equipment for the various boiler systems proposed herein is not actually a primary objective. In fact, the selection of appropriate SO_2-removal systems is a questionable task to undertake at the present time. This view is explained in part by a conclusion recently offered (Ref. 96) by an ad hoc committee convened by the National Academy of Engineering and the National Research Council to study SO_2-abatement processes. They said: "The panel reviewed the status of United States and foreign sulfur oxide abatement and control processes and firmly concluded that, contrary to widely held belief, commercially proven technology for control of sulfur oxides from combustion processes does not exist."

As a result of Government sponsorship, intense interest has focused upon SO_2-removal processes, such that a highly dynamic R&D situation has resulted. It is thus highly possible that any process chosen today may well be soon superseded by newer, more cost-effective processes, or even be discarded because of technical arguments that are not yet adequately defined.

With these constraints in mind, an attempt has nonetheless been made to provide the candidate steam generators with practical APC process designs. Section IV of Appendix B furnishes some of the pertinent information used in establishing the guidelines which were observed.

In approaching this task, the various candidate systems have been divided into two categories, based on the manner in which the flue gases are handled. These are:

- Category I: Combined- or separately-fired furnaces, common flue system. Cases 1, 2, 6, 7, 8, and 9; Modification Nos. 1, 2, 3, 4, and 5.
- Category II: Separately-fired furnaces, isolated flue systems. Cases 3, 4, 5, and 10.

Selection of APC equipment for the Category I boilers must be approached on very nearly the same basis as would be observed for SO_2-emitting (coal-fired) units. In the Category II systems, however, this would not be true for the flue gas emitted by the refuse-fired portion of these systems. The SO_2 levels from these furnaces should be low enough that only particulate management need be considered. Kaiser reports (Ref. 33), for example, SO_2 levels from refractory refuse-incinerators on the order of 15 to 20 ppm.

The next area for consideration is the variation in gas volumes. Furnace availability, refuse availability, and variation in refuse heating value indicate that the combined-fired units will doubtless operate with a much wider variation in total gas volumes, even at a base load, than conventionally fired units. The flow data shown in Table III-4 for Cases 1 and 2 indicate 30 to 50% decreases in gas flow, as the refuse energy input decreases from 100 to 0%. Thus any variation in refuse rate or the stoppage thereof will result in significant changes in gas volumes, even if the fuel value remained constant. This variation, coupled with a typical turn-down of over 50% for power boilers and the actual high variability in the fuel value of refuse, suggests that total variations of 25 to 100% must be anticipated for the gas volumes. This situation does not pose an insurmountable problem in the selection of APC equipment. As pointed out in Section IV of Appendix B, a variable orifice contactor can accommodate variations of this magnitude, provided sufficient static pressure capability is available at the fan for the entire range of flows. The variable orifice contactor can, in fact, be employed to throttle the fan.

Such wide flow variations would cause some concern in the design of appropriate electrostatic precipitators. Overall precipitator performance can be expected to increase at reduced flow-rates, since residence time increases. However, gas flow reductions down to 25% of rating will reduce the effectiveness of conventional gas control devices (turning vanes, etc.) and result in poor gas distribution and, thus, deteriorated precipitator performance. Great care must therefore be taken in the design of the flue work. Three-dimensional model studies of the flue gas system may be required to accomplish this.

The final area of problem definition is the particulate loading in the combustion gases. For the coal-firing components in both system categories, the situation is straightforward. In the suspension firing of coal, approximately 80% of the potential ash in the coal will be released as entrained fly-ash. Despite the fact that some unburned material is present in the coal fly-ash, the 80% factor is reliable. If a greater degree of accuracy is required, more precise relationships are available in the literature (Ref. 97). Using the coal analysis shown in Section III, B, 1 and the gas-flow data given in Table III-4, one would expect approximately 6.0 lbs fly-ash for every 1000 lbs of wet flue gas produced by the firing of coal in any of the systems considered.

Quantification of the particulate loading contributed by refuse combustion is not as straightforward. Stenburg (Ref. 98) and Walker (Ref. 99) have correlated particulate emissions from refuse combustion as a function of grate underfire air. Sternitzke (Ref. 100) presented criteria for air distribution geometries to minimize particulate emissions on refractory units, as well as to reduce refractory maintenance and slagging. However, as pointed out in Appendix B (Section V, C), a number of factors may influence particulate generation rates.

The candidate refuse-combustion systems considered herein are all low-excess-air, water-wall units. The European experience, coupled with the recent domestic conclusions regarding air distribution, indicate that 75% of the total air should be introduced under the refuse bed. This conclusion could have serious implications in the selection of the grate. Some stoker manufacturers might request that as much as 100% of the total air be used for underfire air. The development of reducing atmospheres, coupled with an increased particulate burden, rule out such a disproportionate budgeting of air.

Although the air velocity through the grate is a function of the grate size and geometry, a flow of 55 SCFM/ft^2 grate has been set as the maximum that would be encountered. This compares with about 47 SCFM/ft^2, using the criteria established for the candidate systems of 50% excess air (refuse), 75% underfire air, and a grate stoking rate of 60 lb/ft^2-hr. For mixed municipal refuse, we would expect this upper flow-rate to result in approximately 30 lb fly-ash/ton refuse burned. This can be compared with the median value reported by Niessen, et al, (Ref. 13) of 24 lb/ton of refuse for municipal refuse incinerators of over 50 tpd capacity. Using the air flow data shown in Table III-4, this would result in a loading of about 2.5 lb fly ash/1000 lb of flue gas (wet) generated by refuse in all of the systems equipped with grates.

The fly-ash loading that can be anticipated for systems in which varying stages of the refuse burning occurs in suspension. (Cases 5 through 10 and Modification Nos. 3 and 5) is uncertain. In the same reference cited above, Niessen warns that the fly ash emissions from suspension-fired systems will be considerably higher than from furnaces equipped with agitating grates. This potential problem can be assessed only when actual field experience has been acquired. It should also be borne in mind that most flue gas cleaners are sized on the basis of the volumetric flow that they must accommodate. If particulate loadings exceed the design value, the rate of efficiency loss is usually much lower than would be true if the gas throughput exceeded the design limit an equivalent amount.

b. APC System Possibilities

In Section IV of Appendix B, the combined capability of some particulate collectors to effect gaseous emission control via mass transfer is discussed. The most obvious example is wet scrubbing with alkaline liquor. Particulate collection efficiency of over 99%, and simultaneous SO_2 removal of up to 90% have been previously cited on power boiler applications with direct furnace injection of limestone.

A less conspicuous example is the fabric-filter collector, the basic dust removing capability of which is indisputable. Recent claims have been made of the fabric filter's ability to desulfurize flue-gas following limestone injection into either the furnace or flue work. Any residual desulfurization in the baghouse proper, however, appears highly questionable. The basic problem with the reactive stone injection process is the sulfate and sulfite encapsulation of the reactive particles, which allows only the surface of the particle to react with SO_2. Once the surface is spent, further reactivity requires particle decrepitation in order to expose fresh surface. It appears highly unlikely that such an effect would occur to any significant degree in the bag collector. Moreover, baghouse operating temperatures are usually in the neighborhood of 300°F, which is too low to favor SO_2 reaction with limestone or dolomite.

The high degree of particulate collection efficiency required rules out the application of low energy mechanical or inertial devices. Thus only fabric filters, dry or wet scrubbers of moderate to high energy inputs (>6-in. w. c. pressure drop), and electrostatic precipitators need be considered. The state-of-the-art is well enough developed to permit selection based on a quantitative assessment of the problem. Equally well defined are the economics of particulate collection at high gas-flow rates. Traditional use patterns of particulate collectors support the general concensus (e. g., Ref. 101) that electrostatic precipitators represent the optimum annual cost solution in a high-volume, high-performance situation. Thus, in the present analysis, the electrostatic precipitator has been selected in preference to the baghouse for cleaning the flue gas from Category II refuse-fired furnaces.

For Category I systems and the coal-fired furnaces in the Category II systems, SO_2 as well as particulates must be removed. In Section IV, A of Appendix B, four commercially available desulfurization processes have been reviewed. In terms of present requirements, none has been found to be adequately developed or proved for inclusion in the systems analysis. The principal problems associated with these processes can be summarized as follows:

- Reinluft Process - Highly complicated chemical process hardware and operating expertise are required. Process is not suitable for retrofit situations. Operating and equipment costs are prohibitive.
- Catalytic Oxidation Process - Highly efficient dust removal must be practiced before the flue gas encounters the catalyst. A process temperature of 900°F is specified. Equipment costs are prohibitive.
- Alkalized Alumina Process - Fairly sophisticated chemical process hardware is needed. A source of 1200°F reducer gas is required for the regenerator. Attrition of the alkalized alumina is still an unsolved problem.

- Dolomite/Limestone Injection Process - Pulverized stone injection increases particulate loadings 100 to 150%. Severe plugging problems in the scrubber or contactor section have been encountered. Although favored over other processes, method is considered to be stop-gap (Ref. 96).

The method selected for combined SO_2/particulate removal is the wet lime process. This selection was influenced not only by engineering considerations, but by the growing commercial acceptance the process now appears to be experiencing. The scrubber to be used is of the variable-orifice, venturi type. This type of contactor now appears to have a promising edge over other types, such as those involving dynamic beds. It is recognized that the plugging problems associated with the dolomite/limestone injection process would only be mitigated and not eliminated in using the present, related method.

For the Category I systems and the Category II coal-fired boilers, the APC system shown in Figure III-34 is specified. It basically consists of a venturi scrubber circulating a lime suspension, a spray tower pumping the same absorbent, and a reheat chamber for minimizing stack plume. Using a pressure drop of 6-in. w.c., 99% of the particulates should be removed in the venturi and at least 65% of the SO_2. The spray tower is expected to absorb additional SO_2 for a total removal of 90%.

For the Category II units in which refuse only is fired and the flue gas is handled separately from that from the coal-fired unit, cleaning will be accomplished by electrostatic precipitation alone. The parallel coal-combustion gases would be handled as shown in Figure III-34. Following the cleaning steps, however, the flue gas from the coal-fired unit can be combined with the hotter flue gas from the refuse-fired unit(s). This will result in plume attenuation and permit the use of a common stack. The system is shown in Figure III-35.

Table III-11 provides data on the operating characteristics of the APC system when coupled to candidate systems. Because of the large number of possible arrangements that could be considered (due to capacity and refuse-fraction variables), the table has been limited to six examples.

The wet calcium-based APC systems also offer excellent Cl/HCl emission control, perhaps at levels as high as 98-99%, but lime addition would have to be increased significantly. In some situations, lime consumption might double. The lime consumption values given in Table III-11 are based on SO_2 removal only.

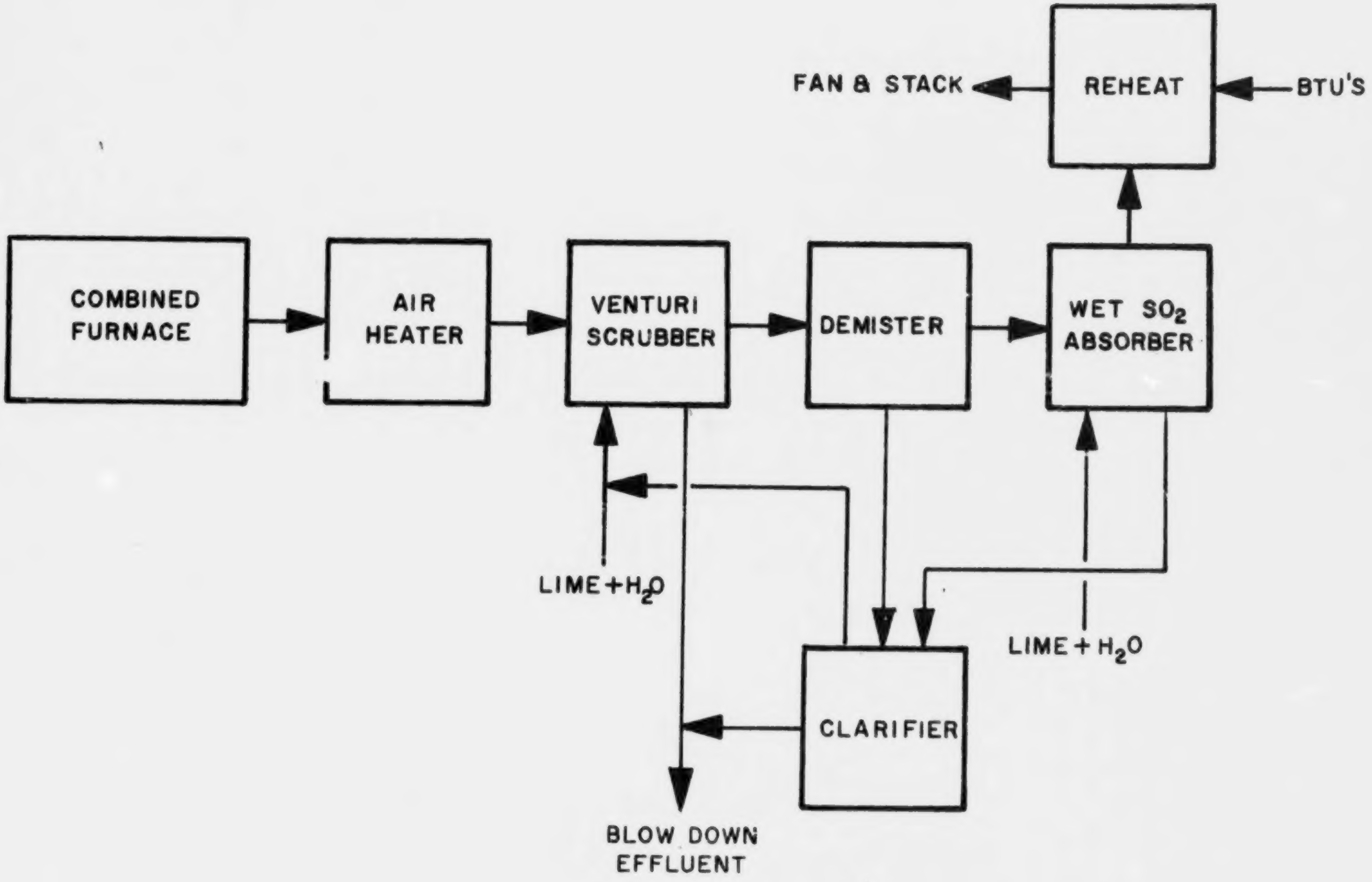

FAN & STACK
REHEAT
BTU'S
COMBINED FURNACE
AIR HEATER
VENTURI SCRUBBER
DEMISTER
WET SO_2 ABSORBER
LIME + H_2O
LIME + H_2O
CLARIFIER
BLOW DOWN EFFLUENT

FIGURE III-34. RECOMMENDED APC SYSTEM FOR COMBINED SO_2 - PARTICULATE REMOVAL

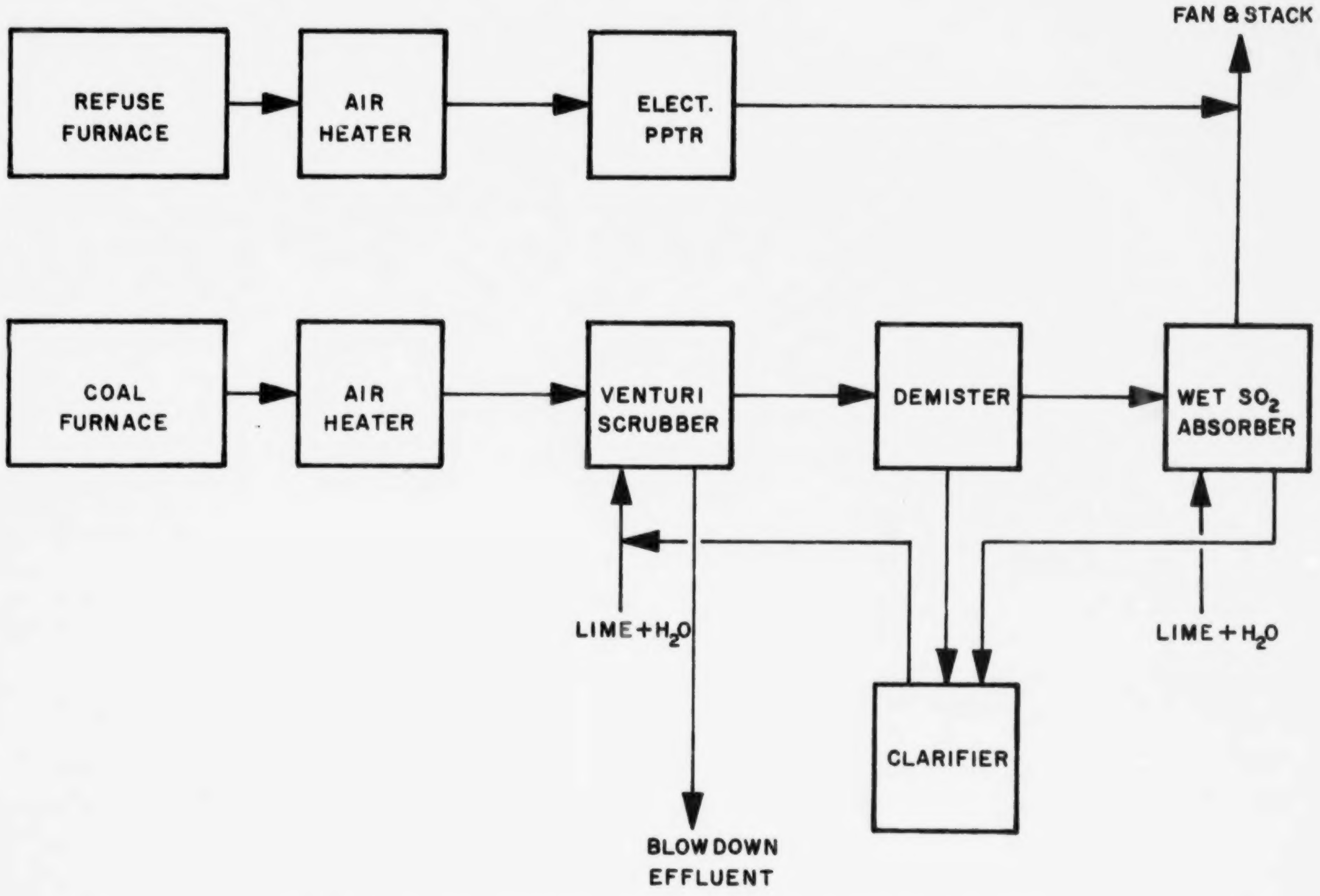

REFUSE FURNACE
AIR HEATER
ELECT. PPTR
FAN & STACK
COAL FURNACE
AIR HEATER
VENTURI SCRUBBER
DEMISTER
WET SO_2 ABSORBER
LIME + H_2O
CLARIFIER
LIME + H_2O
BLOW DOWN EFFLUENT

FIGURE III-35. RECOMMENDED APC SYSTEM FOR CATEGORY II PLANTS

TABLE III-11

CALCULATED OPERATING CHARACTERISTICS OF RECOMMENDED APC SYSTEMS

	Case 3 (400 MW, 25% Refuse)		Case 10 (100 MW, 58% Refuse)		Modification #1 (43.2% Refuse)	Modification #2 (23.6% Refuse)	Modification #3 (42.7% Refuse)	Modification #4 (41.8% Refuse)
	Refuse Unit	Coal Unit	Refuse Unit	Coal Unit	Combined Unit	Combined System	Combined Unit	Combined Unit
APC System	Pptr	Lime System	Pptr	Lime System	Lime System	Lime System	Lime System	Lime System
Flue Gas Flow, 10^3 ACFM ($^{\circ}$F)	178 (575)	990 (300)	343 (450)	147 (450)	342 (450)	640 (450)	241 (450)	252 (450)
Total Liquor Pumping, gpm	-	2214	-	326	795	1432	560	587
Recirculated Liquor, gpm	-	1640	-	216	520	992	366	384
Evaporative Loss, gpm	-	324	-	68	187	350	132	138
Effluent Blow-Down, gpm*	-	250	-	38	88	90	62	65
Total Make-Up, gpm	-	574	-	106	275	440	194	203
Pump HP	-	35	-	5	12	21	9	9
Saturated Gas Flow, 10^3 ACFM ($^{\circ}$F)	-	820 (125)	-	108 (133)	260 (140)	486 (140)	183 (140)	192 (140)
System ΔP, in.-w.c.	2	8	2	8	8	8	8	8
Fan HP	57	1400	110	140	330	620	233	245
Lime Required, 10^3 tons/yr	-	40	-	6	14	26	10	11
Electrical Requirements, kw-hr/yr	590	-	1120	-	-	-	-	-

***Based on nominal 3 gr/ACF fly-ash, 20% solids effluent.**

As will be noted in the next section, the data shown in Table III-11 were not used for the cost modelling effort. It was decided that more conservative bases should be employed for that purpose.

7. Refuse Handling System

a. Design Selection

A variety of possible waste feed arrangements can be considered in preparing the lay-out of a refuse-firing power plant. Choice among such alternatives is not only influenced by practical design and/or cost trade-offs, but by the peculiarities and policies of local waste management programs. The design complications implicit in trying to deal with the latter problem were avoided on the present program by assuming certain operating conditions. These were as follows:

ASSUMED OPERATING CONDITIONS
FOR WASTE RECEIVING

Refuse Composition	See Section II, A, 2; oversize ≯ 5 wt-% of total
Receiving Area	Power Plant
Pickup/Delivery Schedule	6 days per week
Truck Capacity	24 yd^3 (compacted to density of 20 lb/ft^3)
Plant Refuse Consumption	Small Plant = 2000 tpd Large Plant = 8000 tpd
Storage Capacity (80% usage of available volume)	Sufficient for 2 days of operation and assuming settled refuse density to be 12 lb/ft^3: Small Plant = 30,000 yd^3 Large Plant = 120,000 yd^3

The well-tried and extensively accepted method of handling refuse at incinerators and steam generator plants can be seen in various figures of this report. After weigh-in, the collection trucks tip their loads into one or more storage pits contiguous to the furnace where material is outloaded to the charging chute by overhead crane.

In recent years, however, the trend has been to conveyor feed systems. The principal reason for this, as Sutin points out (Ref. 102), is that "they (moving cranes) generate very high capital, operating and maintenance costs." This conclusion was verified on the present study. Thus the basic system selected for the present design development specifically excluded the use of cranes for refuse handling. It was recognized, however, that certain technical problems are still associated with the charging of furnaces with conveyors.

The type of system needed will vary with the mode of firing that is employed in the furnace. This is illustrated schematically in Figure III-36. It can be seen that, for each of the three types of furnaces stoked, the same basic refuse-processing components are required. Thus in developing inputs for the cost model, most of the components were considered to be identical. Exceptions to this were the use of the additional conveyor legs shown in Figure III-36 and of the number and capacity of the shredders specified.

In the discussion of the various system components which follows, the shredding operations are not stressed. These involve fixed-design items that have been discussed previously (Section II, D, 2). It should also be pointed out that the use of metal separators was not included in the systems analysis because of the optional nature of this operation.

b. Weighing Stations

Refuse is usually weighed as it arrives at a refuse reduction plant. The most obvious reason for doing this is the need to establish a reasonable basis for charges to the refuse collector. It can also assist in detecting undesirable waste or loads of material which will require special attention. In terms of boiler or incinerator fuel computation, an accurate knowledge of the weight fired enables comparisons to be made of actual and rated performance. Furthermore, if the source of each load of delivered refuse is known, the data then become a valuable tool for establishing quantity and rate information for specific areas and projecting patterns.

The sizes of the plants proposed in this study are such that the use of automated weighing stations is almost a necessity. As an example, it can be calculated that with a six-day refuse collection schedule, a 2000 ton per day plant must be prepared to accommodate under peak conditions 144 trucks per hour. This is based on the assumption that 80% of the trucks will arrive during two 1-hour periods, each carrying an average load of 6.5 tons of refuse. Manual weighing of each truck would require a sizable investment in scales to handle this traffic and, more importantly, a large annual expense in wages paid to the scale attendants.

There are a number of scale manufacturers capable of providing highly sophisticated, fully automatic weighing systems. In a typical installation, the presence of a truck is detected by a magnetic sensor which activates the scale controls and automatically makes a zero check and

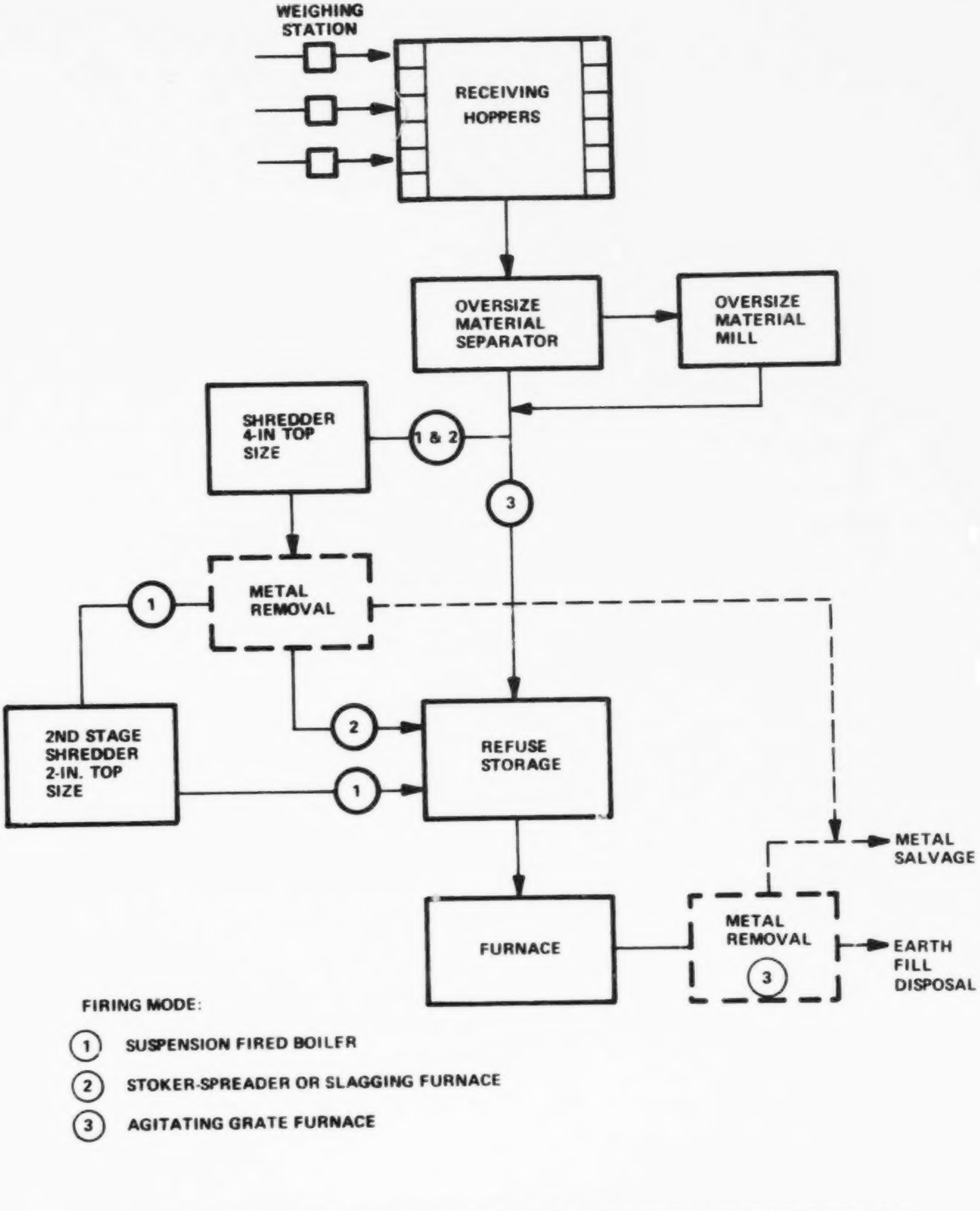

WEIGHING STATION
RECEIVING HOPPERS
OVERSIZE MATERIAL SEPARATOR
OVERSIZE MATERIAL MILL
SHREDDER 4-IN TOP SIZE
1 & 2
3
METAL REMOVAL
1
2ND STAGE SHREDDER 2-IN. TOP SIZE
2
1
REFUSE STORAGE
METAL SALVAGE
FURNACE
METAL REMOVAL
3
EARTH FILL DISPOSAL
FIRING MODE:
1 SUSPENSION FIRED BOILER
2 STOKER-SPREADER OR SLAGGING FURNACE
3 AGITATING GRATE FURNACE

FIGURE III-36. WASTE HANDLING SYSTEMS FOR DIFFERENT TYPE FURNACES

scale adjustment. A gate may then be opened to permit the truck to drive onto the scale where additional sensors and guides assure that the truck is in the proper position for weighing. The driver then places a key or identification card in a slot at the scale house and the weighing cycle is started. A record ticket for the driver is printed and this ticket and the identification card are released to the driver. The exit gate is then opened and the system is ready to repeat the cycle.

Data from the weigh station may be recorded and kept at the weigh station or may be transmitted to any desired remote location. Truck identification, hauler identification, date, time, gross, tare and net weights can be printed and punched onto tape or cards for later data processing and billing.

c. Truck Unloading

In the past, incineration plants usually incorporated unloading arrangements wherein the refuse trucks would dump directly into a storage pit. From there, the contents would be transferred by crane directly to the furnace. Bulky or oversize materials would either be manually separated prior to dumping or be left for the crane operator to locate and reduce by grapple impact. More modern plants, e.g., that under construction for the City of East Hamilton, Ontario, employ active- or live-bottom receiving facilities from which the material can be continuously conveyed to the furnace or to intermediate refuse-conditioning operations. In addition to providing an opportunity for visual inspection of the incoming refuse, the active-bed concept also permits a more controlled feed rate to the material handling and processing systems.

The quantities of refuse which are to be processed by any of the proposed systems in this study are so large that it becomes impractical to depend exclusively on human management of oversized refuse. An error on the part of the responsible individual could easily result in jamming of a refuse feed chute or damage to a furnace grate, and temporary shut-down of a portion of the system. Because of this possibility, direct unloading to the storage pits was ruled out in favor of the use of receiving pits that transfer the feed to the storage structure(s) or shredders by means of conveyors.

The dimensions of the active-bed receiving pit are dependent on the number of unloading stations required to accommodate the anticipated delivery truck arrival rate, which is, in turn, a function of the plant capacity. The results of queueing studies to determine the number of unloading stations required as a function of plant size are presented in Appendix C.

d. Receiving Pit

The refuse receiving installation would consist of an elongated, slope-sided, concrete hopper, along the grade-level edges of which would be the truck receiving stations. The bottom of the receiving pit would consist of a cleated conveyor belt which would agitate and move off the input material to the further processing stages.

Assuming that four minutes is required for each unloading cycle, then the unloading rate per station will be 324 ft^3/min. This is based on the (conservative) assumption that each truck is fully packed (24 yd^3) and that the refuse expands 100% after ejection. On the basis of uniform receiving rate (no peak effect), a 2000 tpd plant would have to host, simultaneously, 4.3 trucks, and an 8000 tpd plant, 17.2 trucks. Rounding off to 5 and 18 positions, respectively, and doubling the required stations to 10 and 36, respectively, in order to reduce queueing during peak times, pit lengths can be estimated. These would be 150 ft for the small and 540 ft for the large plant, if 15 ft were allowed for the width of each station. The basic module, however, would be a 75 ft, 5-station hopper, two of which would be used in small plants and eight in large plants. The use of multiple receiving pits would permit turn-down of the operation during slack period, would tend to reduce back-up if any one system fails, and would permit a more effective location of the pits in large plants with respect to layout of the grounds and nearby roads. A drawing of the hopper facility is shown in Figure III-37. The dimensions shown provide a pit volume of 1300 ft^3/station, which is slightly greater than twice the individual truck capacity. The discharge conveyor would remove material at a considerably faster rate than the maximum truck input rate. The latter rate would prevail of course only when all stations were occupied by trucks requiring the least amount of time to unload (~2 min). Thus the conveyor could be slowed considerably or even completely stopped for several minutes to accommodate downstream problems, without an overfill occurring. The conveyor would be a 72-in. flat-belt type, fitted with 60-in. x 4-in. cleats every 6 ft. Based on the loading characteristics and discharge rate desired, belt speed would be about 530 ft/min.

e. Oversize Material Separation and Reduction

The heterogeneous nature of refuse makes separation or classification operations the most difficult of all material handling problems. Visual sorting of the total incoming refuse load is not considered practical, and the use of rotating screen drums would necessitate that excessively large machines be provided in order to handle the flow rates contemplated. It may not be possible to entirely eliminate human judgment from the sorting process, but even a small degree of automation will greatly reduce the number of decisions that the responsible operator would be called upon to make.

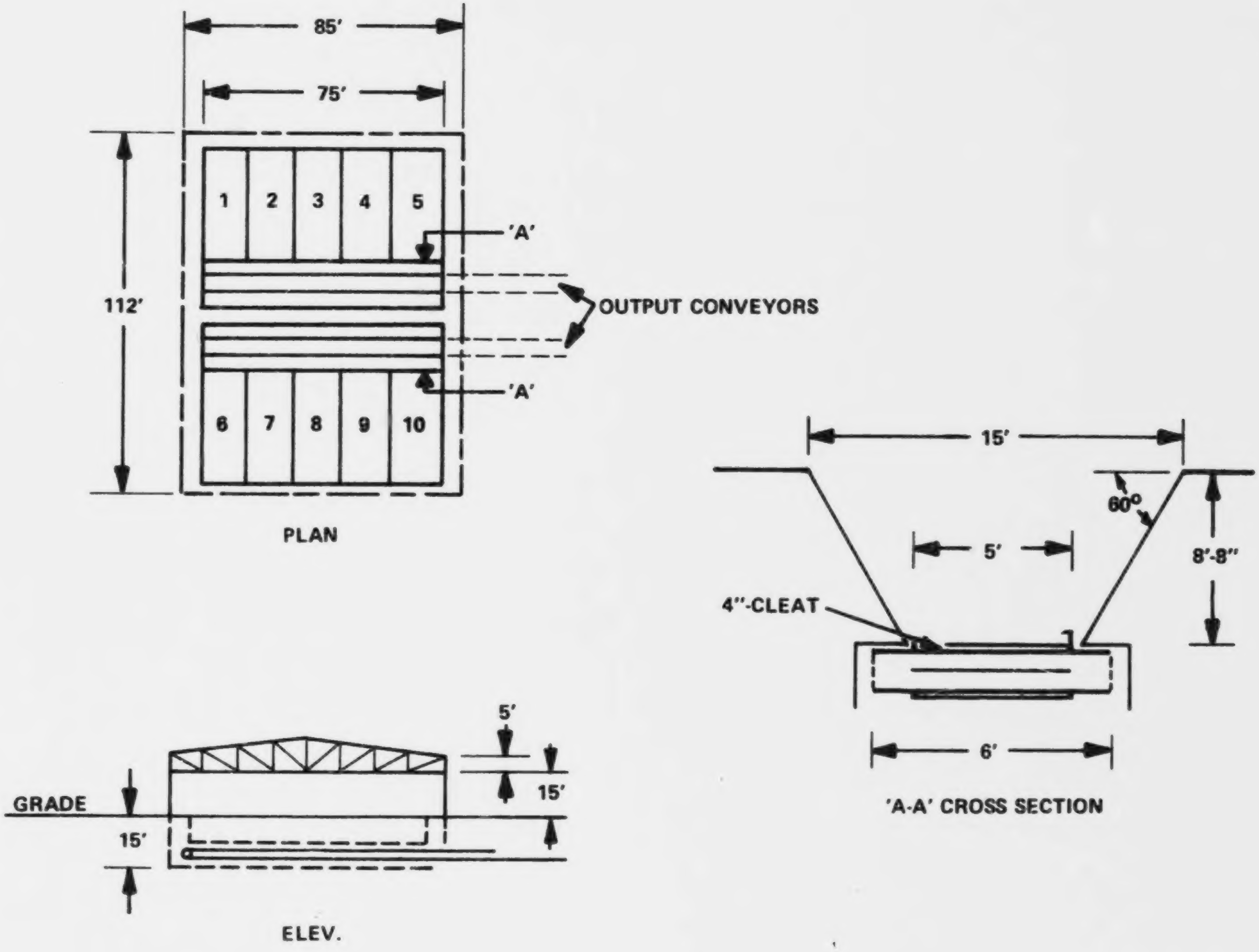

85'
75'
112'
1
2
3
4
5
6
7
8
9
10
'A'
'A'
OUTPUT CONVEYORS
PLAN
15'
60°
5'
8'-8"
4"-CLEAT
6'
'A-A' CROSS SECTION
5'
15'
GRADE
15'
ELEV.

FIGURE III-37. RECEIVING PIT LAYOUT

Variable speed control on the active bed of the tipping floor system will make possible a nearly constant flow of refuse to the transport conveyor. With a fairly uniform refuse depth on the conveyor, mechanical, optical, or beta-radiation detectors can be used to sense objects that extend above a predetermined height. Automatic dumping devices could then be used to divert the oversized refuse to the bulk-reduction stage. Some flat, oversized objects will pass through this scanner undetected, such that their diversion would have to be accomplished by manual control at the discretion of the receiving pit attendant. Because of uncertainties of costs, however, this type of equipment could not be included in the systems designs. There it was assumed that oversized refuse would be separately delivered, a common practice in many LMA's.

The reduction of oversized refuse is an essential step in the refuse handling process regardless of what methods of transport, storage, or firing are to be used. The equipment to be employed for the size reduction of bulky objects is not expected to produce an output of small particle dimensions, but only to furnish a size that will be acceptable to the furnace charging system, the refuse storage and retrieval system, or other shredding equipment. Because the shredder must be sized to accept fairly large pieces, it will usually have a throughput capacity that is greater than the feed rate, which, in oversized articles, is only about 5% of the total refuse delivered.

f. Storage Facilities

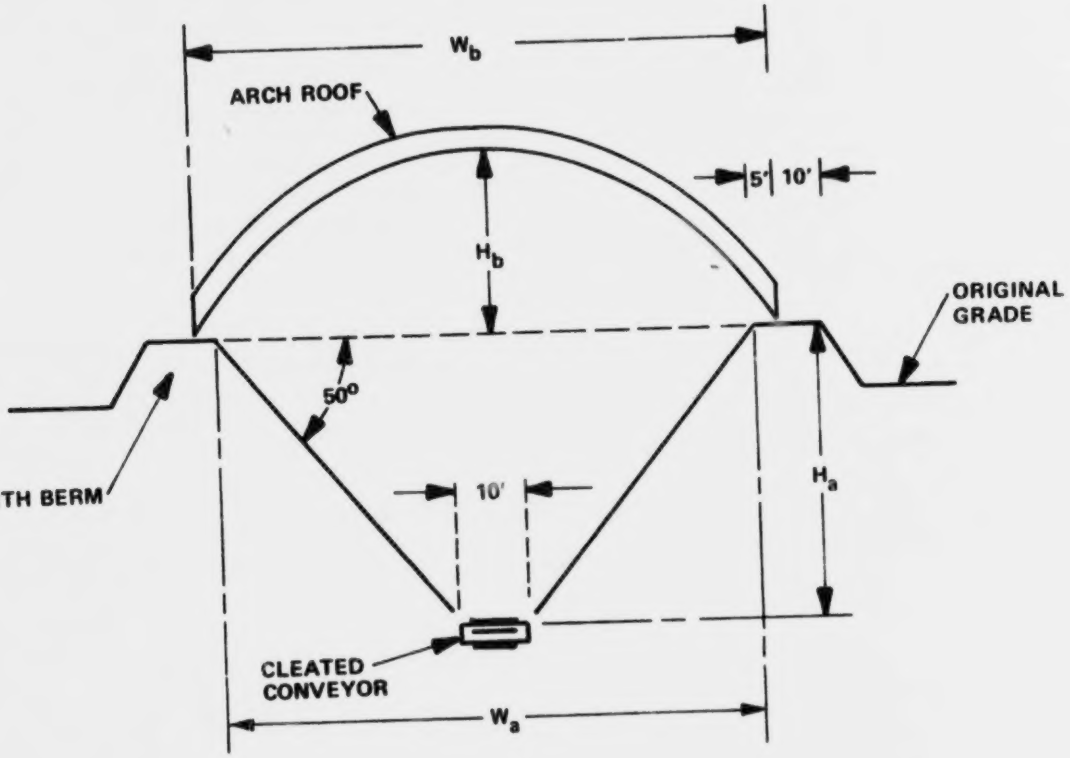
(1) Design Factors

Experience has shown that refuse exhibits poor flow properties and tends to develop stoppages in storage structures equipped with bottom-release devices. This effect is frequently encountered when voids form over the output chute, hopper, or conveyor trench. The remaining stalled mass is then said to be "bridged" or "arched." A related problem is the inactivation of entire vertical portions of the pit contents that are not standing directly over a point or line of bottom discharge flow. It is thus essential that the bottom of the pit be designed so that possible footings for arching or piling effects are minimized.

In developing designs for the storage structures, another factor that was taken into account was land availability. The two types of pits considered were designated low and high profile, based on their suitability for power-plant grounds with ample and limited land availability, respectively.

(2) Low Profile Storage Pit

A drawing of this concrete-lined, metal-roofed structure is presented in Figure III-38. Not shown there is the location of the input conveyor. This device would enter the structure on the centerline just


W_b
ARCH ROOF
5'
10'
H_b
ORIGINAL GRADE
50°
EARTH BERM
10'
H_a
CLEATED CONVEYOR
W_a

CONSTRUCTION SPECIFICATIONS

	SMALL PLANT	LARGE PLANT
NUMBER OF PITS	2	4
CAPACITY PER PIT, yd^3	15,000	30,000
LENGTH OF PIT, ft	155	195
GABLE WALL SURFACE, ft^2	3,300	4,800
OTHER DIMENSIONS, ft		
W_a	77.5	97.5
W_b	87.5	107.5
H_a	39	53
H_b	31.3	37

FIGURE III-38. LOW PROFILE REFUSE STORAGE PIT

below the top of the roof and travel the full length of the pit. Rakes would be suspended from the roof over the conveyor run to remove the load in an even pattern. One 72-in. input belt would be used for each of the small plant storage-pits and two belts of that width in the larger pits.

The discharge conveyors would be operated at 600 ft/min in both sizes of pits. This fast rate would produce a certain degree of agitation in the pit bottoms. The belt width required would be 72- and 96-in. for the small and large pits, respectively. For costing purposes the following conveyor requirements were assumed:

CONVEYOR SYSTEM FOR LOW PROFILE REFUSE INSTALLATION

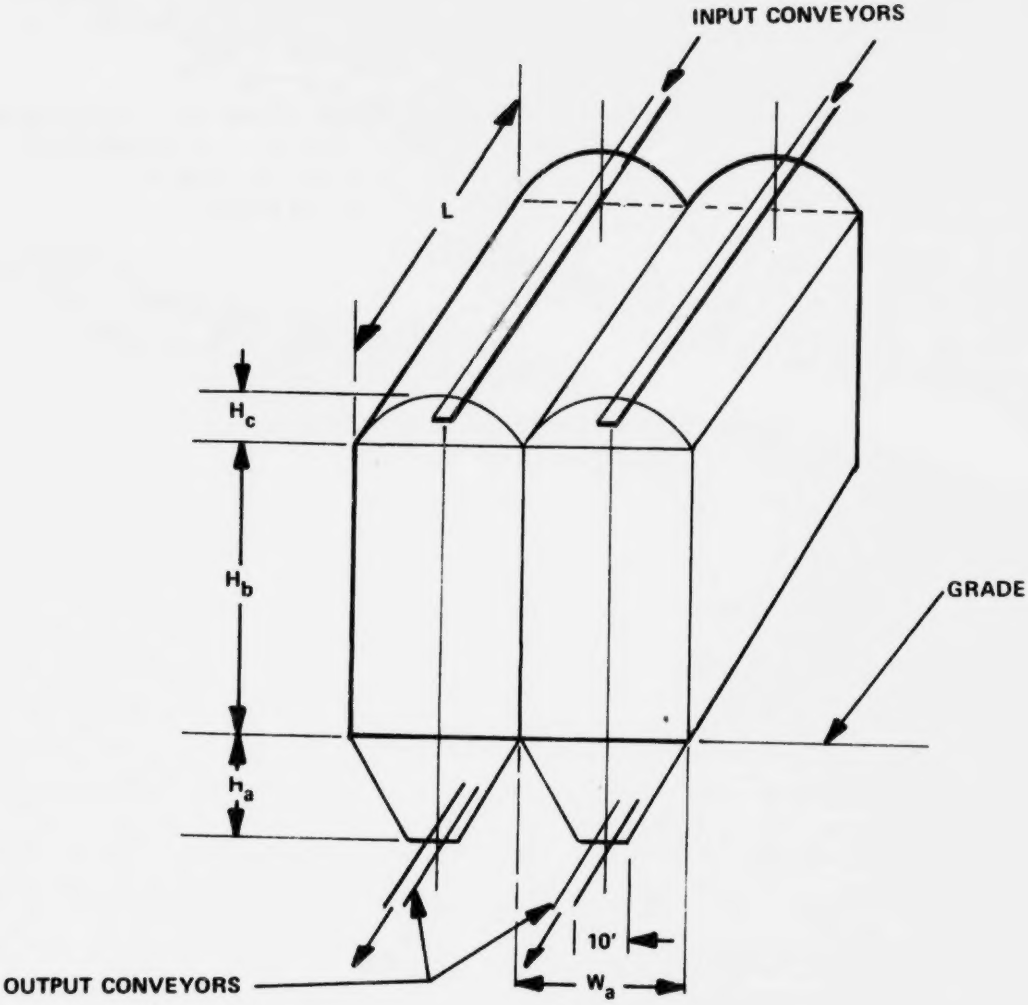
	Location	Length, ft		No. of Runs		Total Length of Conveyor needed, ft	
		(A)[1]	(B)[2]	(A)	(B)	(A)	(B)
1.	Receiving Pit to Shredders	270	270	1	4	270	1080
2.	Shredders to Storage Pit (inclined)	120	120	2	8	240	960
3.	Along Roof of Storage Pit	160	200	2	8	320	1600
4.	Along Bottom of Storage Pit	160	200	2	4	320	800
5.	From End of Pit Bottom to 4 ft above grade (25° Slope)	114	142	2	4	228	568
6.	End of Item 5 to Charging Chute	300	300	2	4	600	1200

1) Small Plant (2000 tpd)

2) Large Plant (8000 tpd)

(3) High Profile Storage Structure

A sketch of this low floor-area system is shown in Figure III-39. This concrete-walled building would also be covered with a metal, arched roof. By nesting the structures, one wall would be eliminated in the twin (small plant) installation and three in the quadruple (large plant) arrangement. In the latter case, two 72-in. feed conveyors would be used in each unit instead of the single 72-in. conveyor shown in Figure III-39 for small plant requirements. Except for length, the discharge conveyor belts would be the same widths as for the low profile system and would also move at 600 ft/min. The conveyor requirements assumed for high profile construction are as follows:


INPUT CONVEYORS
L
H_c
H_b
H_a
GRADE
10'
W_a
OUTPUT CONVEYORS

CONSTRUCTION SPECIFICATIONS

	SMALL PLANT	LARGE PLANT
NO. OF BUILDINGS	2 (AS ABOVE)	4 (ALL COMMON WALL GANGED)
CAPACITY PER BLDG, yd^3	15,000	30,000
DIMENSIONS, ft		
W_a	40	50
H_a	18	24
H_b	50	60
H_c	16	20
L	165	218

FIGURE III-39. HIGH PROFILE REFUSE STORAGE BUILDING

CONVEYOR SYSTEM FOR HIGH PROFILE REFUSE INSTALLATION

	Location	Length, ft		No. of Runs		Total Length of Conveyor needed, ft	
		(A)[1]	(B)[2]	(A)	(B)	(A)	(B)
1.	Receiving Pit to Shredders	270	270	1	4	270	1080
2.	Shredders to Storage Building (inclined)	150	150	2	8	300	1200
3.	Along Roof of Storage Building	170	220	2	8	340	1760
4.	Along Bottom of Storage Building	170	220	2	4	340	680
5.	From End of Item 4 to 4-ft above Grade (25° Slope)	170	220	2	4	340	800
6.	End of Item 5 to Charging Chute	300	300	2	4	600	1200

1) Small Plant (2000 tpd)

2) Large Plant (8000 tpd)

As a simplification, Figure III-39 shows the discharge belts as being positioned at the bottom of the bin hoppers. Actually, these belts would be located to one side in parallel-aligned conveyor tunnels. Material from the bin would be transferred to the conveyor by means of a slot feeder, such as used in coal handling systems. This device would consist of a rotating rake mounted on a tracked machine that would travel back and forth along the side of the hopper bottom and claw material from the latter, throwing it onto the discharge conveyor. This arrangement is preferred because in a high profile storage structure the vertical load on a bottom-mounted conveyor would probably impede its operation.

(4) Silo Configuration

In the low and high profile structures just described, configurations were adopted that would impart good flow characteristics to the contents. In the first case, steeply angled walls would be employed so that no horizontal surfaces would be presented to furnish footings for refuse bridging or vertical piling. In the latter (high profile) case, where a hopper bottom must be used, the occurrence of flow hold-ups is minimized by virtue of the narrow, elongated shape of the building. This greatly increases the ratio of active or live-bottom area to cross-sectional area.

The corollary to the above logic would be that a structure having a square or circular cross-section would not be advised. These shapes would accept comparatively short bottom-conveyors and thus afford a low active- to cross-sectional-area ratio. If, however, a storage shell with regular cross-sectional dimensions were equipped with bottom-sweep machinery (e.g., chain-dragged buckets), acceptable flow characteristics could result. Because a cylindrical geometry is the most compatible with such (usually rotary) devices, an analysis was conducted based on a silo-type storage system. This is shown in Figure III-40. This structure was costed on the basis of the use of a metal skin (1/8-in. thick; 5.1 lb/ft^2) because concrete forming in this shape is more expensive. Vertical stays were specified, each ten feet apart up to the top ring-girder. Drawings of the silos were then submitted to a manufacturer of bottom-sweep equipment for the development of cost estimates. Their hardware was considered to be priced closely with similar installations produced by competitors. When these costs were added in, the following comparisons were derived:

COMPARATIVE COSTS OF HIGH AND LOW PROFILE
SYSTEMS AND LIVE-BOTTOM SILOS

System	Total Building Costs, 10^6 \$	
	Small Plant (2 units)	Large Plant (4 units)
Low Profile	0.69	1.95
High Profile	0.57	1.55
Silo Configuration	1.43	4.44

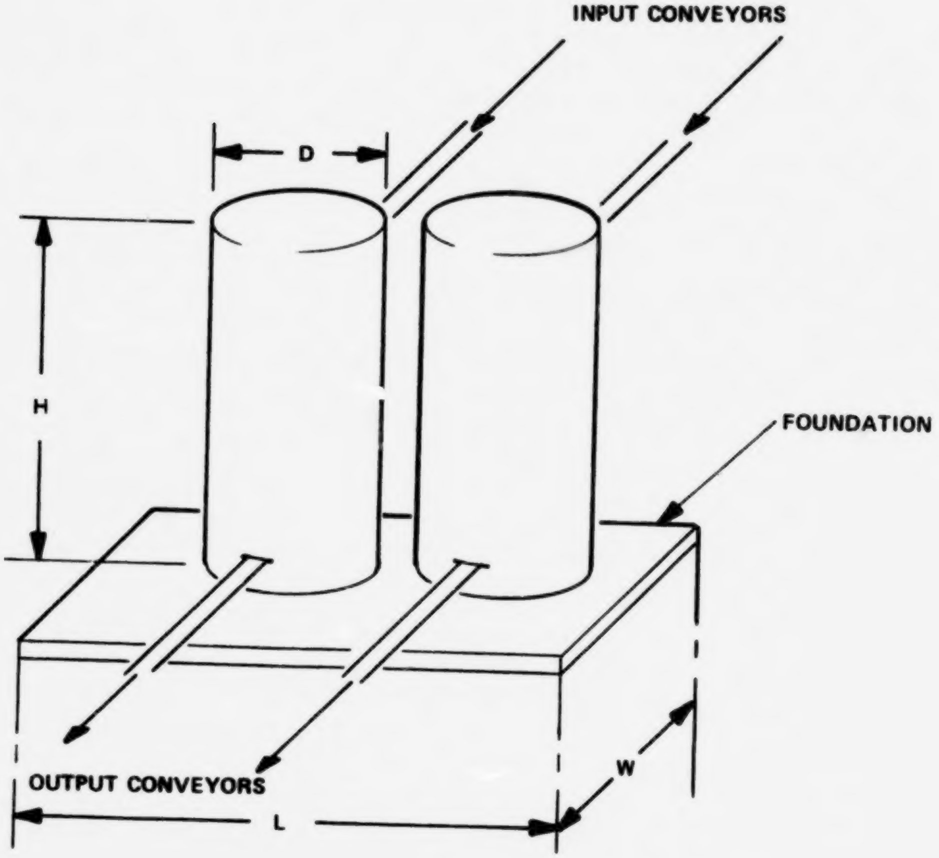
As pointed out in Appendix C (Table AC-12), the above costs include a significant contingency allowance for the estimates generated by the staff of the present study. None, however, were added to the commercial bids submitted for the sweep equipment.

In view of the much higher costs of refuse storage facilities equipped with bottom-sweep machinery and the uncertainty that such equipment will operate satisfactorily with unground refuse, such designs were omitted from the cost model. The above cost information should, however, be of value to those who would prefer a more conservative design approach.

C. EVALUATION OF SELECTED ENGINEERING DESIGNS

1. Cost Model

A cost model has been developed to estimate the net disposal cost that could be achieved with each of the alternative concepts described in the preceding section. The cost model (described in detail in Volume II, Appendix C) has been derived to permit the evaluation of each candidate concept under a broad range of operating conditions. In general, it was felt that no one concept would prove to be universally applicable under all conditions. As a result, the object of the cost analysis was to determine which were the superior candidates and the conditions under which they were optimum.


INPUT CONVEYORS
D
H
FOUNDATION
W
OUTPUT CONVEYORS
L

CONSTRUCTION SPECIFICATIONS

	SMALL PLANT	LARGE PLANT
NO. OF SILOS	2 (AS ABOVE)	4 (ON SAME FOUNDATION)
CAPACITY PER SILO/yd^3	15,000	30,000
DIMENSIONS, ft		
W	110	130
L	220	520
H	96	126
D	94.5	113

FIGURE III-40. REFUSE STORAGE SILO

a. Assumptions

The cost model developed for this program is based on the basic assumption that the power company using refuse as a fossil fuel substitute would be a regulated public utility with privately owned equity financing and subject to all applicable Federal, state, and local taxes.

An important parameter affecting the net cost of refuse disposal in a new combined firing plant is the value of the power generated in that plant. If the utility had no need for additional capacity when it installed the plant, the value of the power generated by it would be the marginal cost of the fossil fuel saved by substituting refuse. If, however, the utility required the additional capacity, the value of the power would be the same as that from a conventional plant of the same size that had been built under contemporary cost conditions. Because most utilities are faced with increasing power demands, the latter case has been assumed. Thus, in computing the power credit for combined firing plants, the cost of power for an analogous conventional plant was applied. In addition, it was assumed that the fossil plant would have to meet the same particulate and SO_2 emission standards as the combination-fuel plant, and the cost of emission control equipment was included in both designs.

The capital annualization rate ranged between 14 and 16 percent, depending on the assumptions made concerning interest rates, allowable return on investment, and equipment life. The factors considered in this rate are as follows:

Factor	Basis
Capital Recovery	The capital recovery factor is based on a 7 percent return and the estimated equipment life.
Insurance	The annual cost of insurance is estimated to be 0.25 percent of the total capital investment.
Federal Income Tax	This cost is based on a 55 percent tax on profit and assuming half of the total capital investment is borrowed at 6 percent.
Other Taxes	The annual cost of state and local taxes is estimated to be 1.9 percent of the capital investment.

For example, assuming an average equipment life of 20 years, the annualization rate is found to be 14.7 percent as shown below:

Item	Annualization Factor as a Percent of Capital Cost of Equipment
Capital Recovery	9.43
Insurance	0.25
Federal Income Tax	3.10
Other Taxes	1.90
Total Annualization Factor	14.68

In computing the net disposal cost, a nominal plant factor of 80% was used, primarily because it was assumed that the combined firing plant would be operated as a base load plant. Thus, if the plant was designed to fire 1000 tons per day, the cost of disposal was based on 800 tons per day. The sensitivity of other assumptions concerning plant factor was also examined.

A nominal coal cost of 31¢/million Btu was assumed for this analysis. The sensitivity to coal costs in the range of 22 to 36¢/million Btu was investigated.

As adopted earlier, the nominal heating value for refuse was again assumed to be 4460 Btu/lb, and the heating value of coal (with a slight rounding) was assumed to be 12,020 Btu/lb. The effect of these assumptions on the net disposal cost was also analyzed.

b. Cost Model Structure

The cost models for both the combined firing and conventional power plants have been developed in an analytical (equation) format for use in a computer cost and optimization program developed for this project. The cost model for computing the net disposal cost of refuse has been divided into 5 categories: capital costs, capital annualization rates, operating and maintenance costs, power credit, and residue disposal costs. The base date for all cost factors used is July 1969.

The capital cost model considers all costs associated with the fixed plant and equipment required to operate the combined firing plant, involving:

- Land and land rights
- Structures and improvements
- Boiler plant equipment
- Auxiliary boiler equipment
- Turbine-generator equipment
- Accessory electrical equipment
- Air pollution control equipment
- Waste handling equipment
- Engineering and construction supervision

The capital annualization rate model considers all factors required to compute the annualization rate for a regulated public utility, including the following factors:

- Rate of return
- Equipment life
- Federal income tax rate
- Interest rate
- Debt to equity ratio
- Insurance
- State and local taxes

The operating and maintenance costs are estimated considering:

- Plant factor
- Operating labor
- Maintenance labor
- Fuel costs
- Supplies and maintenance materials
- Electrical power
- Cooling water

As discussed in the previous section, the power generating credit is computed by determining the cost of power in an analogous conventional fossil fuel plant of the same size, fuel costs, plant factor and debt structure as the combined firing plant.

The residue disposal costs were calculated on the assumption that the material could be disposed of in a specially operated residue disposal site and that the residue would be hauled to the disposal site in 15-ton payload vehicles, each operated by a single driver.

Tables III-12 and III-13 summarize the cost model assumptions and structure for a typical case. Table III-12 shows the assumptions made for this particular case and its operating characteristics. In this case it was a 400 MW plant deriving 25% of input heat from refuse and processing 2232 tons per day of solid waste. Table III-13 summarizes the costs for this particular case, showing a total capital cost of $67,080,000, an effective annualization rate of 14.6% and a net disposal cost of $0.57 per ton.

The costs of disposal in a combined firing plant are often compared to that of sanitary landfilling. Such a direct comparison is, however, often misleading since a sanitary landfill system often involves considerable hauling of refuse at a cost of 20 to 30 cents per ton-mile, much of which may be avoided in a combined firing disposal system. In addition, the cost of operating a sanitary landfill for the residue may be significantly less than that for non-putrescible refuse ($0.75/ton vs $1.50/ton). In order to avoid the ambiguity of a direct disposal cost comparison, a model has been constructed to permit comparisons of total haul and disposal costs.

When the cost of transporting the collected refuse 3.5 miles to the plant is considered, the total haul, processing, and disposal cost would be $2.21 per ton. This is the figure that should be compared to the haul and disposal cost of alternative systems. For example, consider a sanitary landfill at $1.50/ton and a haul cost of 23¢/ton-mile (equivalent to a 3-man crew operating a 20 cu yd packer truck at 30 MPH). If the landfill site was more than 3 miles from the center of population, the total haul and disposal cost would be greater than the $2.21/ton cost of this example.

c. Cost Model Results

The objective of this section is to present the cost results of systems that appear applicable to the problem of power generation utilizing solid waste as a fuel, and to delineate the operating characteristics of these systems in sufficient detail to permit additional evaluation of promising systems. The conceptual design of each system that was studied was synthesized from consideration of the most acceptable methods of incinerating

TABLE III-12

SOLID WASTE/FOSSIL FUEL POWER PLANT (SEPARATELY FIRED ECONOMIZER)

POWER PLANT CHARACTERISTICS

Plant Power, MW	400
Plant Factor	0.80
Ratio of Heat from Refuse Combustion to Total Heat Input	0.25
Design Waste Load, tpd	2,790
Average Waste Load Processed, tpd	2,232
Number of Turbines	1
Number of Steam Generators	1
Number of Refuse Fired Economizers	3

COST PARAMETERS

Rate of Return on Capital, %	7
Income Tax Rate, %	55
Other Taxes, % of Capital Costs	1.90
Insurance, % of Capital Costs	0.25
Interest on Borrowed Capital, %	6
Unit Cost of Land, $/acre	10,000
Fraction of Capital Borrowed, %	50
Steam Generator Efficiency (with Fossil Fuel), %	87.0
Steam Generator Efficiency (with Waste Fuel), %	65.0
Electrostatic Precipitator Efficiency, %	98.0
Wet Scrubber Efficiency Particulates/SO_2, %	98.0/90.0
Heating Value of Waste, Btu/lb	4,460
Heating Value of Coal, Btu/lb	12,020
Cost of Coal, ¢/10^6 Btu	31
Residue Disposal Costs	
Landfill, $/ton	0.76
Transportation, ¢/ton-mile	23

TABLE III-13

COSTS OF A SOLID WASTE/FOSSIL FUEL POWER PLANT (SEPARATELY FIRED ECONOMIZER)

CAPITAL COSTS, 10^6 $

FPC Codes	Description	
310	Land and Land Rights	0.69
311	Structures and Improvements	5.47
312	Boiler Plant Equipment	35.28
314	Turbine-Generator Equipment	13.75
315	Accessory Electrical Equipment	2.87
316	Misc. Power Plant Equipment	0.59
	Air Pollution Control Equipment	4.04
	Waste Handling Equipment	1.81
	Engineering and Inspection	2.59
	Total Capital Cost	67.09

ANNUAL COSTS

Annual Capital Cost, 10^6 $ (Effective Annualization rate, 14.6 percent)	9.77
Water Cost, 10^6 $	0.01
Operating Labor, 10^6 $	0.62
Maintenance, 10^6 $	1.73
Coal Cost, 10^6 $	6.76
Residue Disposal, 10^6 $	0.36
Total Annual Costs, 10^6 $	19.23
Annual Credit for Power Generated, 10^6 $	18.76
Quantity of Waste Burned, 10^3 ton/yr	815
Disposal Cost, $/ton	0.57
Transportation Cost (3.50 Mile Haul Radius), $/ton	1.64
Total Cost, $/ton	2.21

refuse and still be compatible with power generation. The design concepts represent systems significantly different in design and operation so as to be representative of all the alternatives compatible with existing and future operating conditions and technology.

The detailed cost model and cost data presented in Appendix C were incorporated into a computer program to determine the optimum design and operating point of a waste-fossil fuel power generating plant. The various design configurations studied in the program are described in Section III, B. These candidates are summarized for convenience in Table III-14.

As stated previously, the credit for power generation is computed from the cost of a conventional coal-fired plant operating with the same regulated rate structure, debt to equity ratio, interest rates, plant factor, and fuel costs as the combined firing plant This model is summarized in Figure C-17 of Appendix C. For example, for a 300 MW plant with a fuel cost of 31¢/million Btu, the model shows the power generation credit to be 7 mills/kw-hr.

Eight of the ten candidate design concepts were examined in detail using the computer cost model. Case 8 was found after preliminary investigation to be almost identical in cost to Case 2, except for refuse processing requirements, and Case 9 was excluded after preliminary study on the basis of unrealistically high costs.

As a general rule, the costs were computed at power generation rates between 50 and 500 MW, at 50 MW intervals*, and refuse fractions (percent of heat from refuse) at 20, 40, and 60%, except where design considerations required the use of other specific values. Thus it was possible to have 30 different cost options for a single case. Figure III-41 shows the effect, for Case 2, of varying the plant power capacity with a constant refuse fraction. It is apparent that, for this case (and most cases), the effect on disposal cost by plant power capacity is small because the credit for generating power is decreasing as the plant capacity increases. The effect of refuse fraction for Case 2 is shown in Figure III-42 for a constant 300 MW power level.

As will be shown, Cases 2, 3, 4, and 10 are the most promising alternatives. The disposal costs for these 4 cases are shown in Figure III-43. Figure III-44 shows the disposal costs for Cases 1, 5, 6, and 7. Based on this comparison, the latter group was excluded from further consideration. Case 8, which had been considered as being nearly identical (except for refuse grinding) in cost with Case 2, was also dropped

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*For clarity, data in the present text are shown only for the 100, 300, and 500 MW sizes.

TABLE III-14

TEN STEAM GENERATOR DESIGNS SUBMITTED TO COST MODEL ANALYSIS

Case	Description
1	Separate Furnaces with Common Convective Passes
2	Combined Furnaces
3	Separately Fired Economizer
4	Separate Fossil Fuel Superheater (Saturated Steam from Waste)
5	Separate Fossil Fuel Superheater (Partial Superheat from Waste)
6	Suspension Fired Furnace
7	Spreader Stoker
8	Slagging Furnace
9	Arch Furnace
10	Arch Furnace and Separate Fossil Fuel Superheater

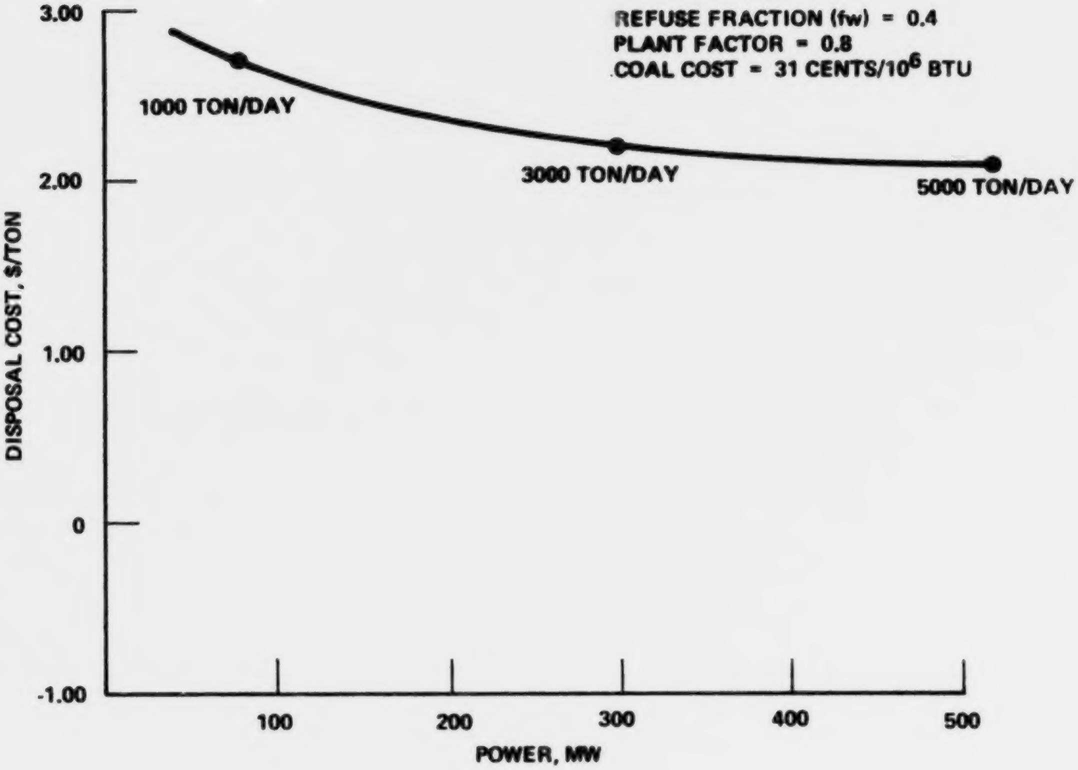


FIGURE III-41. DISPOSAL COST AS A FUNCTION OF PLANT CAPACITY · CASE 2

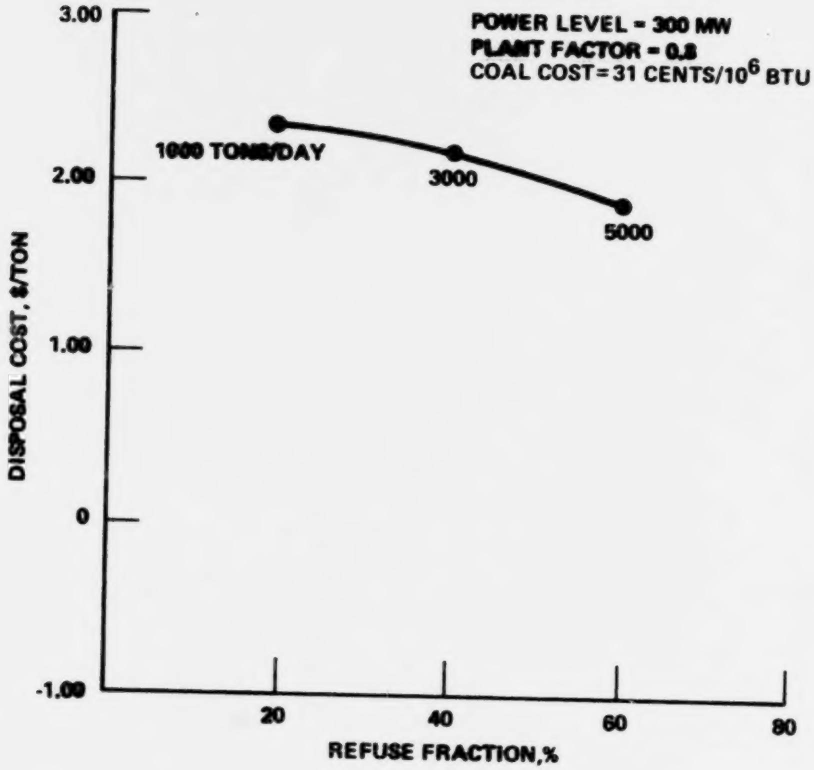


FIGURE III-42. DISPOSAL COST AS A FUNCTION OF REFUSE FRACTION - CASE 2

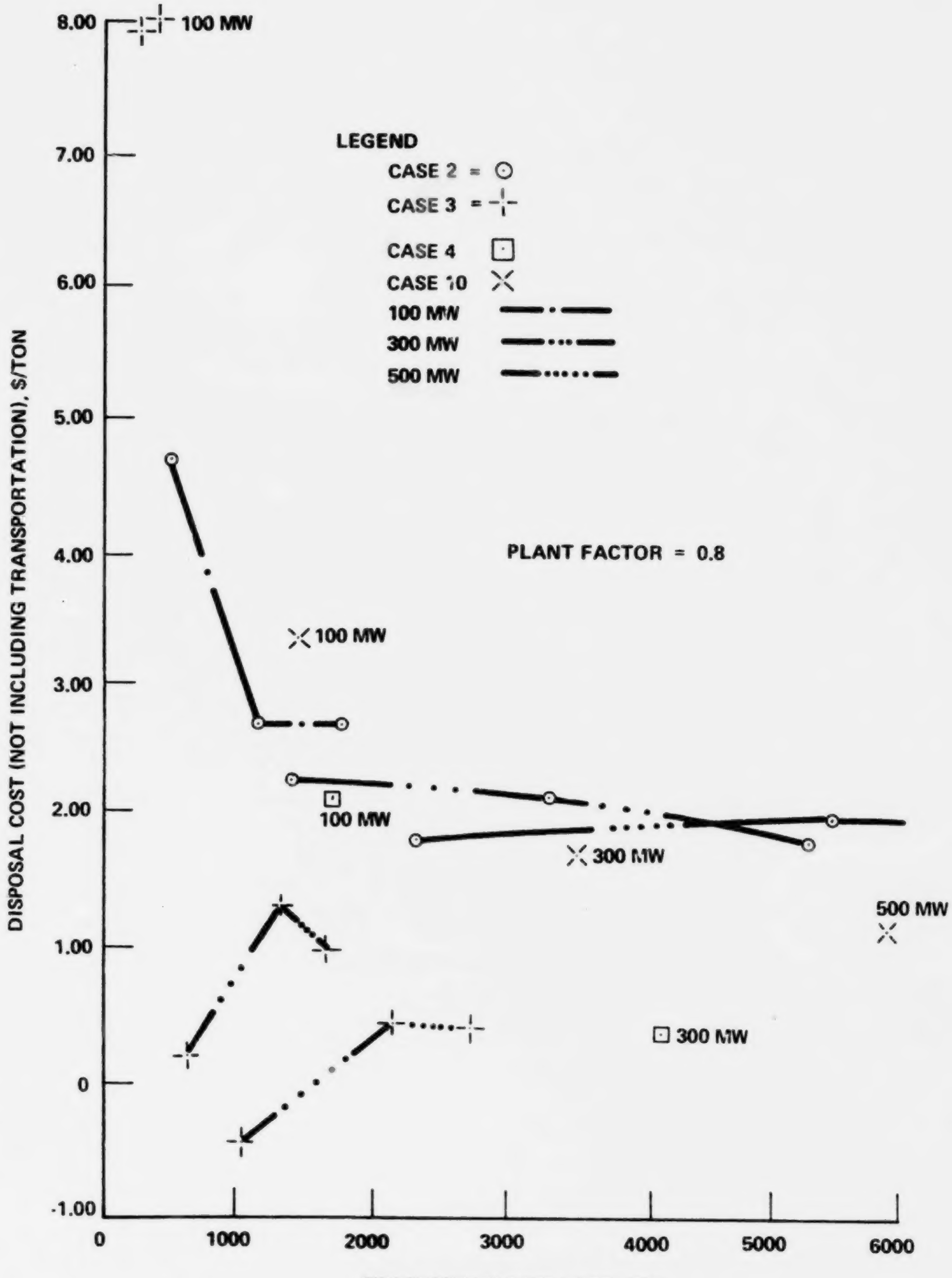


FIGURE III-43. NET DISPOSAL COST VERSUS WASTE LOAD - CASES 2, 3, 4 AND 10

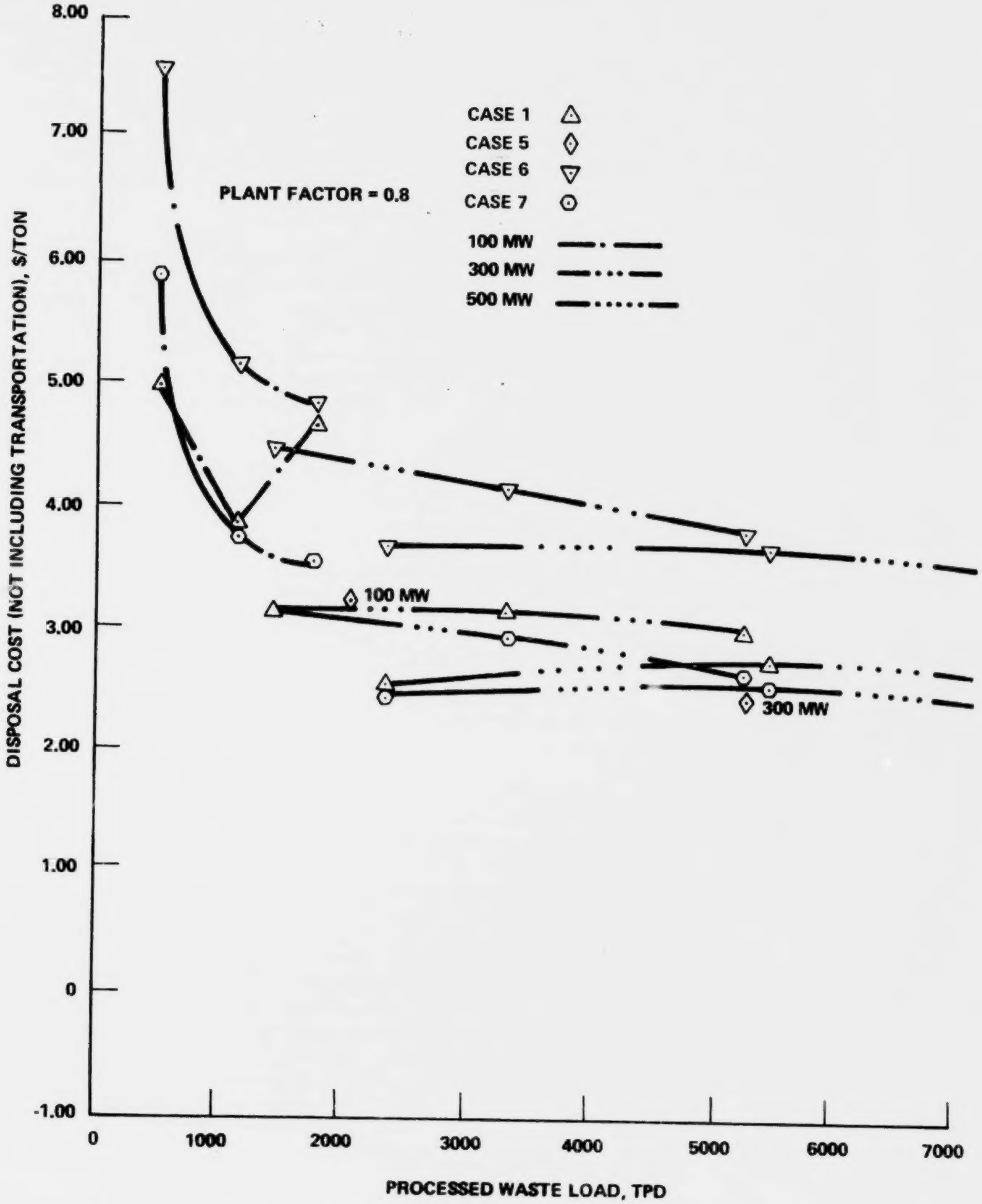


FIGURE III-44. NET DISPOSAL COST VERSUS WASTE LOAD - CASES 1, 5, 6 AND 7

at this point. When the additional costs for refuse preparation were added in, the case was no longer competitive. Because of discontinuities in the cost model resulting from the requirement for discrete numbers of steam generators and turbines, the costs do not always form smooth curves.

In most cases the model indicates that the unit disposal cost decreases with increasing waste load. Since the cost of transporting the collected waste to the combined firing plant can add significantly to cost, these costs should be considered. Based on a procedure described in Appendix C, the transportation costs for two cities (New York and St. Louis) were estimated as a function of waste load; the result is shown in Figure III-45.

To ascertain the optimum system, the net disposal plant cost and transportation cost were summed and a net total waste disposal cost for each design configuration was determined. Results from this procedure indicate that no one particular steam generator design configuration is optimum. The best design is a function of power level and waste load. For example, Figure III-46 shows the results for Case 2 at 300 MW using the St. Louis transportation costs. The curve indicates a shallow optimum between 1000 and 2000 tpd.

The selection of an optimum design configuration must be based on the consideration of the amount of refuse to be disposed, the need for additional power capacity and other factors. The cost analysis did not indicate that any single design configuration was best over the entire range of power levels and waste loads. At power capacities between 200 and 500 MW and waste loads between 500 and 2500 tpd, Case 3 appears to be the best choice. For waste loads in the same range and power capacities of less than 200 MW, Case 2 appears to be optimum, although Case 4 is also competitive. For waste loads greater than 2500 tpd and power requirements greater than 200 MW, it would appear that both Case 3 and Case 4 are the best candidates. Under certain conditions (not shown in Figures III-45 and III-46), Case 10 becomes competitive for capacities less than 150 MW.

Current conventional power plant practice is to provide approximately 1.3 kw per capita and to install plants of sufficient capacity to provide for a three to five year growth in electrical requirements. Since the average annual growth in power demand is approximately 7%, this results in installing plants of approximately 0.3 to 0.5 kw per capita. Using this criterion and a limit of 500 MW per plant, it is evident that more than one installation would be required in areas of large population. Using a generation rate of 5.5 lb per capita day and the power capacity criteria stated above, a minimum cost line was determined as shown in Figures III-47 and III-48. These lines reflect the effect of population density, and consequent transport costs, on optimum plant type and cost; they apply respectively to densities characteristic of New York and St. Louis. The steam generator design configuration, waste fraction, and installed capacity are also shown in the figures.

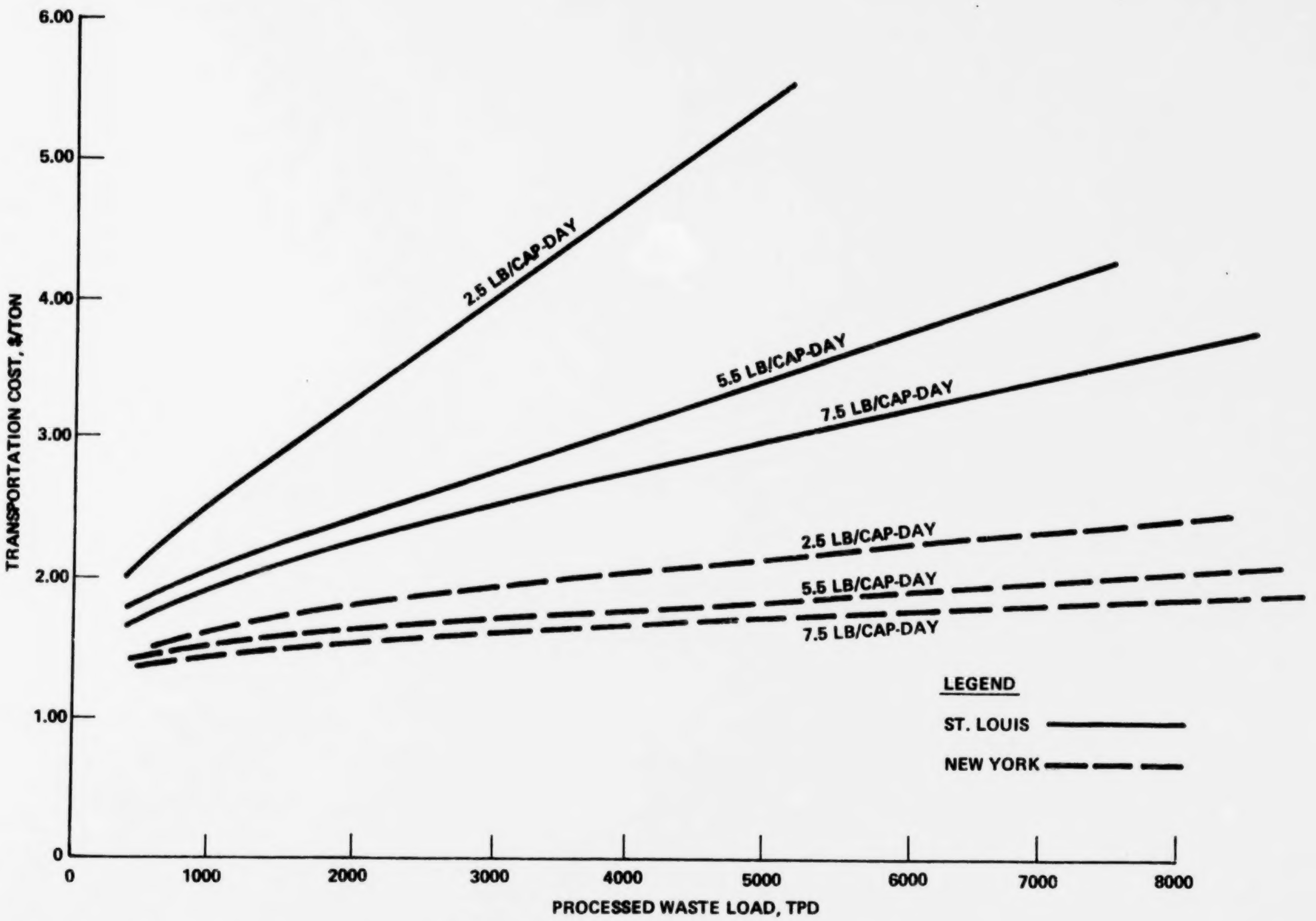
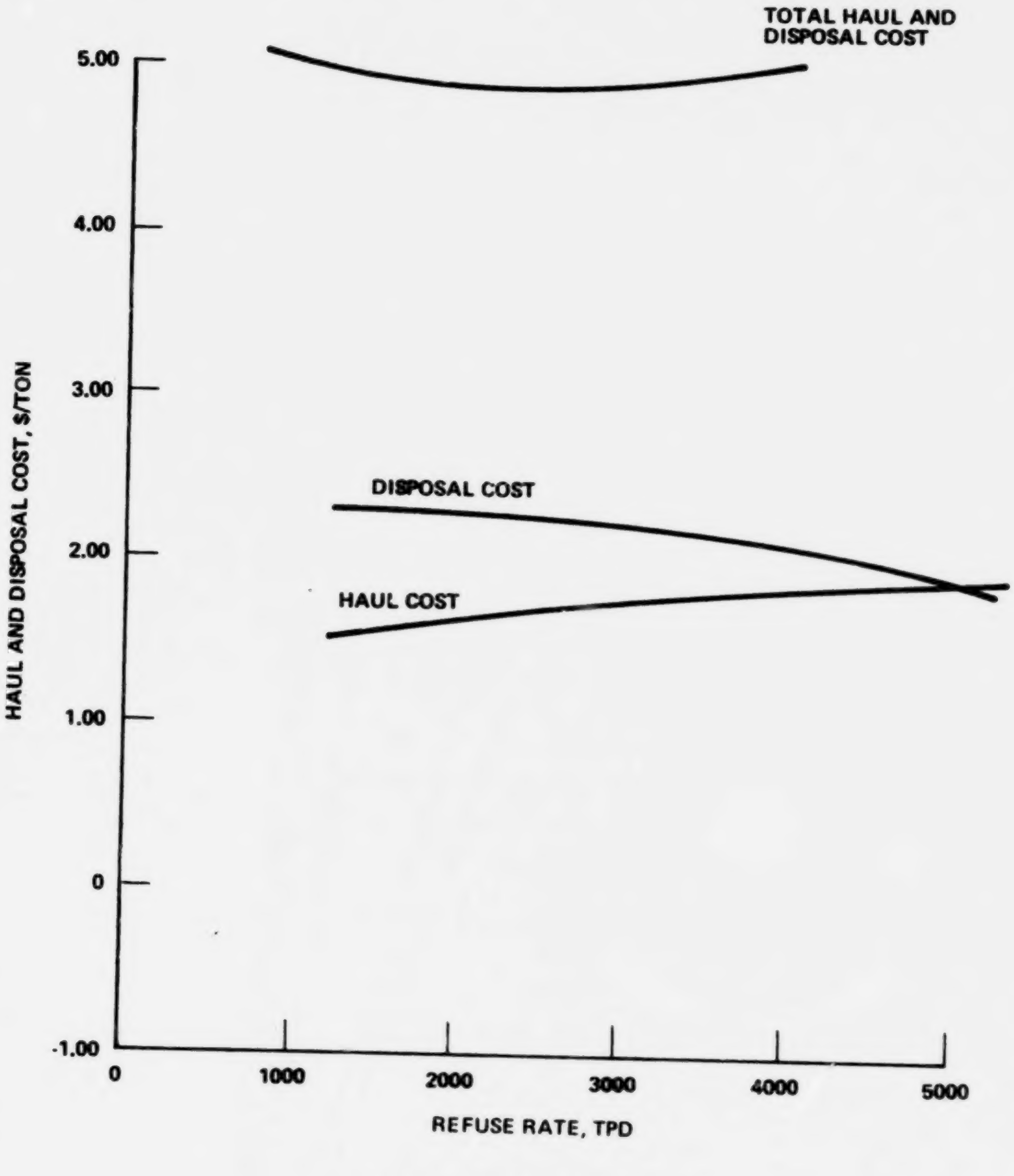


FIGURE III-45. TRANSPORTATION COST AS A FUNCTION OF WASTE LOAD



(CASE 2 - 300 MW, ST. LOUIS)

FIGURE III-46. EFFECT OF HAULING COST ON OPTIMUM PLANT SIZE

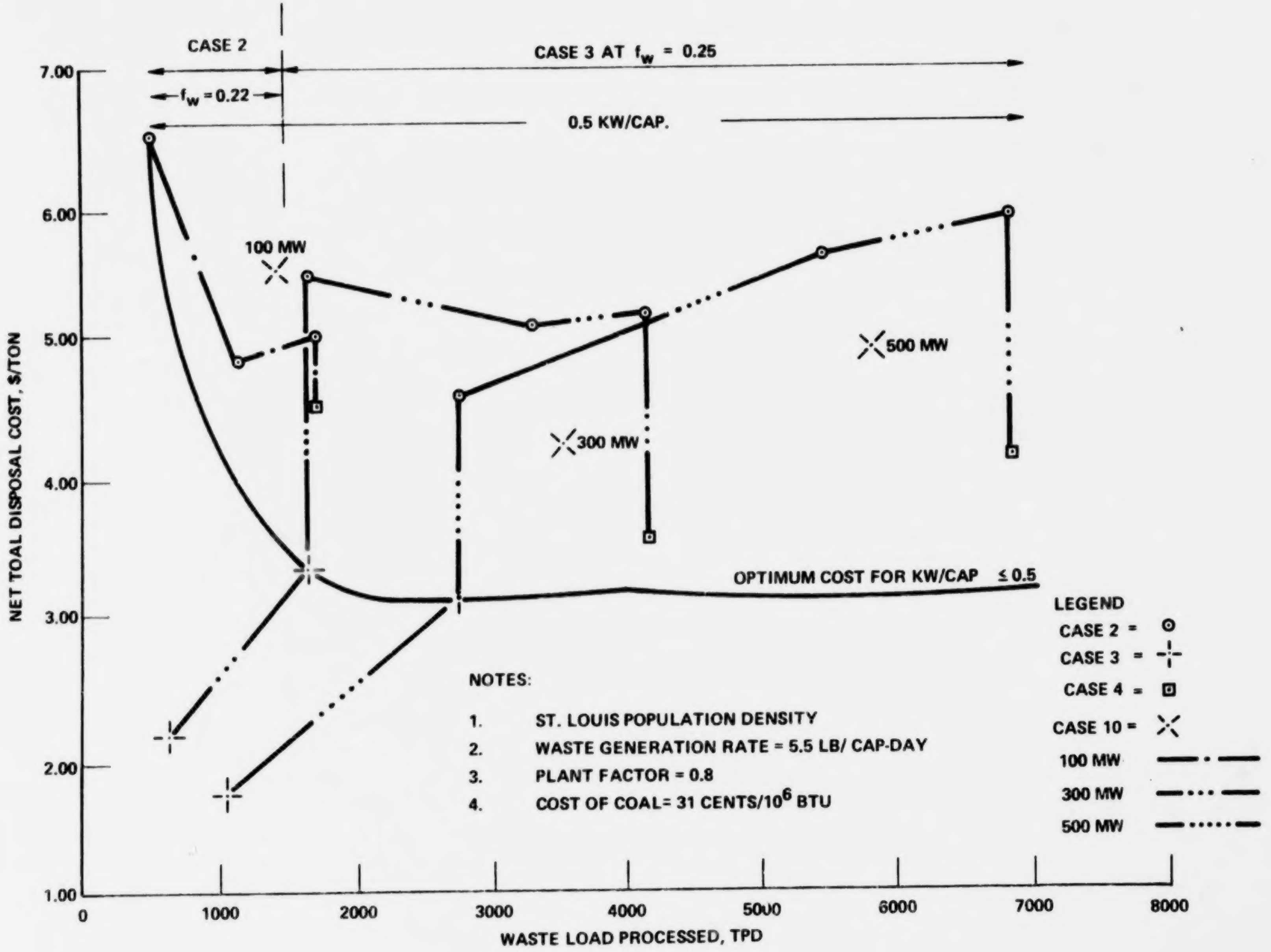


FIGURE III-47. OPTIMUM NET TOTAL DISPOSAL COST VERSUS WASTE LOAD (ST. LOUIS AREA)

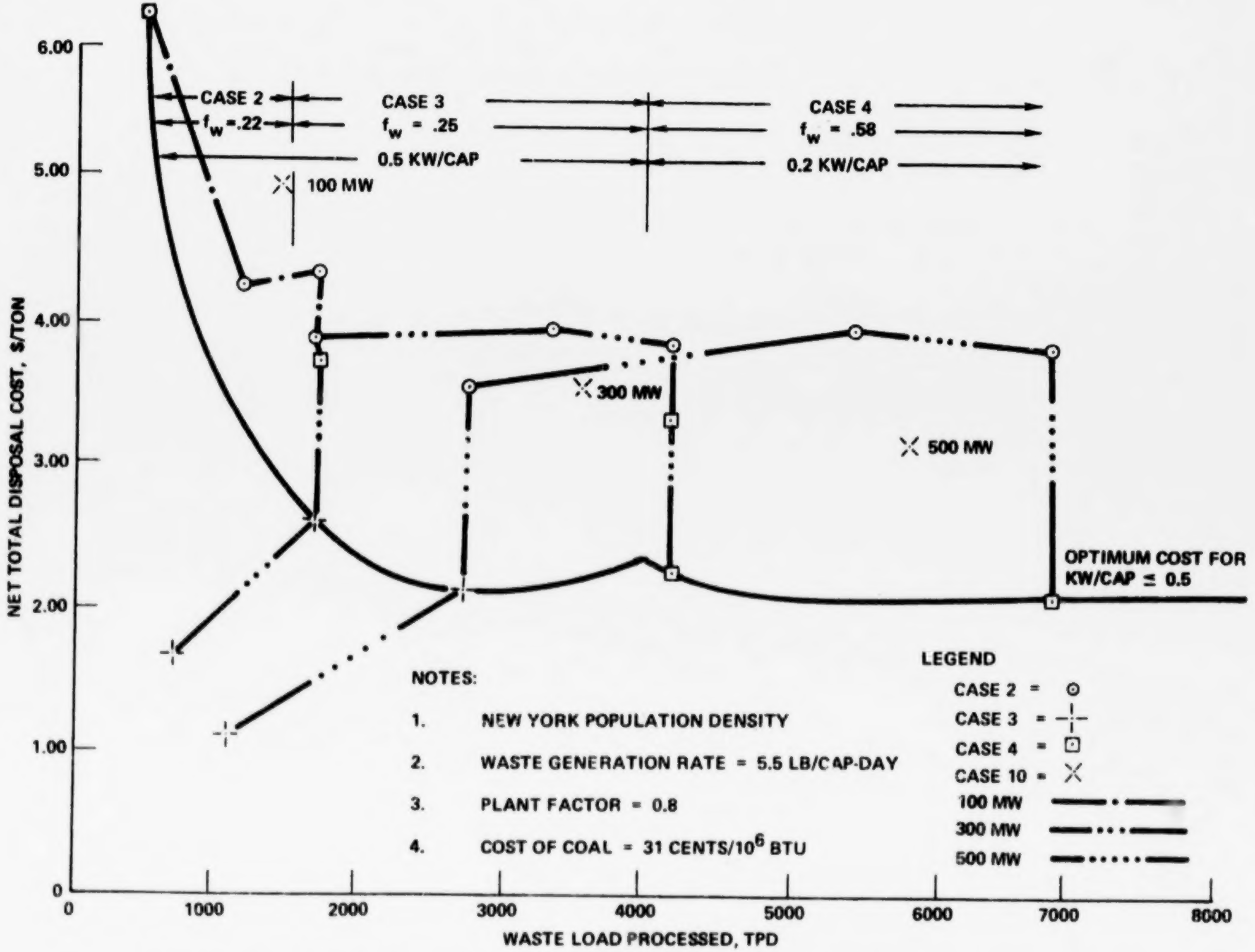


FIGURE III-48. OPTIMUM NET TOTAL DISPOSAL COST VERSUS WASTE LOAD (NEW YORK AREA)

Each of the three broken lines in Figures III-47 and III-48 represent the locus of minimum cost designs for a given power generation level (100, 300, and 500 MW), as a function of the input waste load. However, these lines do not reflect the fact that the electrical power generation capacity and the refuse disposal capacity must be matched to the supporting population. The solid curve represents the locus of minimum cost designs where the waste load and power capacity have been matched to supporting population. For example, in Figure III-47 it is shown that while Case 3 is the minimum cost design at 500 MW and 1000 tpd, the population required to use 500 MW of additional electrical capacity would produce more than 1000 tpd and as a result this design combination is not compatible with the requirement of matching refuse capacity with power capacity. The figure shows that the best design for a 500 MW plant would be Case 3 with a refuse capacity of 2900 tpd.

Figures III-47 and III-48 show that Case 2 is the optimum design configuration for waste loads less than 1000 tpd, beyond which Case 3 becomes optimum. In the more densely populated case of New York City (illustrated in Figure III-48), Case 4 becomes optimum after 4000 tpd. The optimum curves in these figures illustrate the effect of multiple plants for handling large waste loads.

All of the results presented thus far have been based on a plant factor of 0.8 and on coal costing 31 cents per million Btu. To ascertain the effect on cost and design of varying these reference values, the cost and optimum design were determined at 0.6 plant factor and at 22 and 36 cents per million Btu a the cost of coal. The effect of the reduced plant factor is to increase cost by approximately 15 cents per ton at low waste fraction (10%) and 40 cents per ton at the high waste fraction (60%). However, when the optimum cost is selected based on the limit of 0.5 kw per capita plant capacity, this cost increase becomes very significant; e.g., at 2000 tpd, the optimum cost at 0.8 plant factor is $2.35 per ton whereas at 0.6 plant factor the optimum cost is $3.80 per ton, both using cost at 31 cents per million Btu. This condition is caused by not being able to use Case 3 design for the 0.6 plant factor because of the limit on the waste fraction of 25%; i.e., this limit does not permit a sufficiently high power level at this waste load condition. The consequence then of a 0.6 plant factor is that Case 10 or Case 4 would be the optimum design, over the 1000 to 6000 tpd range, with the net disposal cost varying from $5.10 to $2.50 per ton.

The unit cost of coal influences the credit allowed for power generation. In addition, the unit cost of coal affects the total cost of the waste burning plant, although not as significantly.

The effect on net disposal cost of varying the unit cost of coal is influenced by the waste fraction and power level, as shown in the table below:

Refuse Fraction (f_w), %	Power Level, MW	Unit Cost of Coal - ¢/10^6 Btu 22	 31	 36
		Net Disposal Cost, $/ton		
10	100	8.47	9.30	9.75
20	100	6.08	6.15	6.19
10	500	1.17	1.12	1.08
25	500	2.56	2.14	1.90
60	500	4.03	3.64	3.42

At power levels in excess of approximately 100 MW, the net disposal cost decreases with increasing unit coal cost regardless of the waste fraction. This is because the cost of the conventional power plant increases significantly with increasing coal cost at the higher power levels (see Figure C-17 of Appendix C) and hence there is a substantial savings in substituting waste for coal. At low power levels, the waste fraction must be in excess of 20% before increasing unit coal costs result in decreasing disposal cost. This is because, at low power levels, the conventional plant is not affected as greatly because of the relatively high fixed costs, and only after a substantial amount of coal is replaced by waste is the cost savings achieved.

The cost model was also used to investigate the sensitivity to several additional assumptions.

The first assumption investigated was the heating values of 12,020 Btu/lb and 4460 Btu/lb for coal and solid waste, respectively. Other (arbitrarily selected) combinations of heating values for both fuels were therefore analyzed. The purpose was merely to establish the magnitude of the effect changes in these parameters (and the consequent changes in firing rates) would have on disposal costs. The following tabulation indicates the results:

	Solid Waste Heating Value, Btu/Lb	Coal Heating Value, Btu/Lb	Net Disposal Cost, $/Ton
Reference	4460	12,020	2.21
	5000	11,000	2.13
	4000	13,000	2.32
	5000	13,000	2.14

It is evident that the net disposal cost is not sensitive to changes in the heating value of coal and that a change in solid waste heating value causes a small variation in the net disposal cost.

Another assumption that was evaluated was the rate of return on capital. The following table shows the effect on net disposal cost by using an 8% rate of return compared to 7%:

	Rate of Return, %	Net Disposal Cost, $/Ton
Reference	7	2.21
	8	2.64

It is apparent from the above tabulation that the cost of disposal is very sensitive to the rate of return on capital.

d. Cases Selected for Optimization

From the foregoing discussion it is clear that, depending on the waste load and installed capacity, three steam generator designs offer the optimum configurations. These are Cases 2, 3, and 4. As pointed out, Case 2 would be preferred only for low waste loads, thus making it a questionable choice for design optimization. It is also evident that even in the few instances where Case 4 is competitive, it is not significantly better than Case 3. Thus the latter emerges as the favored candidate. Because Case 3 is optimum in the range between 300 and 500 MW, the size selected for design optimization was set at 400 MW.

As discussed in the section immediately following, a second candidate, of the suspension-firing type, was also selected for design optimization. A major cost item in suspension firing is the cost of shredding the refuse. For example, the cost model predicts shredding costs for Case 10 of approximately $2.65 to $2.30 per ton over the range of 100 to 500 MW. Because, with future experience, this particular cost factor may decrease and potential variation in other cost data occur, it was deemed advisable to include a candidate of the suspension-firing type.

Within the suspension-fired class of steam generators (Cases 5 through 10), Case 10 clearly emerges as the favored configuration. Based on Figures III-47 and III-48, a size of about 150 MW would appear optimum for this case, although the distinction is not sharp. The actual capacity selected was 100 MW. This was done to provide a design for the lower capacity range, Case 3 (400 MW) already fulfilling the larger size requirements. In the following section the design optimization of these two candidates is discussed. The resulting systems are then again costed to take into account the more detailed design information that is developed.

2. Optimization of Selected New Plant Designs

a. Introduction

An initial objective of the present systems analysis was the development of preliminary engineering designs of (1) a new plant for combination firing of fossil fuel and refuse, and (2) a new power generating incinerator with fossil fuel used as an auxiliary fuel. In the first type plant, the heat input from fossil fuel and refuse would logically fall within some range of fuel combinations determined by refuse availability, power requirement, and other extrinsic factors. In the latter type plant, the fossil fuel would, at most, constitute a minor portion of the heat input and, possibly, even be used only on a stand-by basis.

During the study, however, the use of more than 60% heat input from refuse was found to be inadvisable. In the case of boilers equipped with agitating grates, unacceptable steam-flow variations would certainly occur at high refuse rates. Regardless of the mode of firing, however, requisite plant steam conditions and layout would also be far from optimal. As shown in Figure III-49, a typical map of fuel requirements for different plant sizes and steam conditions*, a refuse heat input above 60% would necessitate an 850 psig non-reheat cycle and the use of an excessive number of steam generators. The Figure III-49 fuel map incorporates the limitation that any given plant would handle no more than 8, 000 tpd of refuse. This was done primarily in consideration of refuse collection logistics and the projected refuse production rates of the six LMA's given in Section II, A.

In consideration of these design constraints, both combined and auxiliary fossil-fuel firing, though not clearly distinguishable, were considered to be achievable in a single system.

The type-categorization was also structured so that it would be addressed to advanced-design features. Approached from this viewpoint, the goal became one of developing designs for:

- a system in which the extant combined-firing practices would be optimized;
- an optimum system based on steam generator configurations not yet tested with refuse fuel.

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* A second map for isolated-flue systems could also be included, but would only lead to the same conclusions developed here.

CONDITIONS

REFUSE COMB. EFFICIENCY = 69.0%
COAL COMB. EFFICIENCY = 84.0%
MAXIMUM REFUSE RATE / UNIT = 1000 TPD

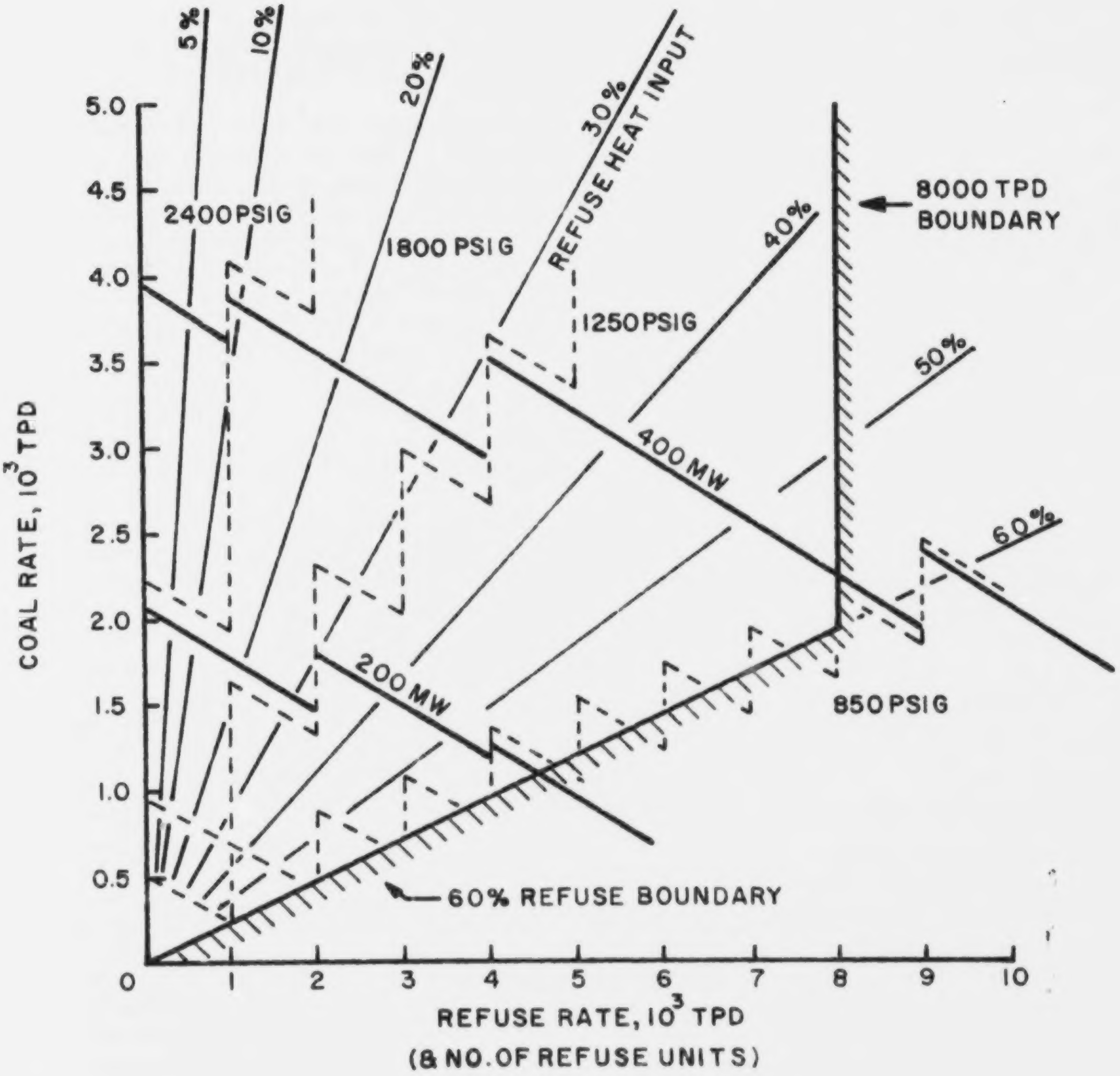

FIGURE III-49. FUEL REQUIREMENTS FOR COMBINED FIRING (BLENDED FLUE GASES)

In terms of the ten candidate systems, an obvious dichotomy emerged. The first four cases essentially fit the first category, while cases 5 to 10 belong to the second. In a loose sense, this dichotomy can be said to differentiate between the (tried) agitating grate type systems and the (untried) suspension-fired systems.

Based on the results of the previously described cost modeling, the configurations and plant sizes favored for preliminary engineering design development are Case 3 - Separately Fired Economizer (400 MW) and Case 10 - Arch Furnace With Separate Superheater (100 MW).

As shown in the systems analysis, maximum heat input for the Case 3 design is about 25% refuse. The limitation is basically due to the steam cycle and not the firing mechanism (agitating grate). A plant of this design could be designed for almost any heat input from refuse between 0 and 25%. As will be shown later, it is possible for a plant designed for 25% heat input from refuse to operate at intermediate refuse rates. The fuel ratio for Case 10 is also determined by the steam cycle and has been set at about 50% heat input for each of the fuels. The basic steam generator design data are given in Section III, B.

b. Separately Fired Economizer

(1) Preliminary Engineering Technical Factors

As in the original conception of this design, feedwater would be taken from the last stage feedwater heater, be further heated in a refuse-fired economizer, and then be evaporated, superheated and reheated in a conventional fossil-fuel fired steam generator as shown in Figure III-50. For a 400 MW plant a 2400 psig steam cycle would be used (see Figure III-49) wherein three parallel, separately fired economizers would be connected in series to a single coal-fired steam generator and one turbine-generator set. It is recalled that this concept was originally used at Munich South, Unit 6 (Ref. 103). A map of the fuel requirements, as determined in the system analysis, is shown in Figure III-51. The boundary and conditions have been previously described.

(2) Economizer

Feedwater is heated to slightly below the saturation temperature corresponding to the feedwater pressure. It is recalled that the tube metal temperatures are below the threshold where high temperature fouling and corrosion due to refuse might be anticipated. Low temperature corrosion is avoided by venting the flue gases at a temperature of 575°F, considered to be above any acid dewpoint. This temperature was selected on the basis of the heating surface available for cooling the flue gas.

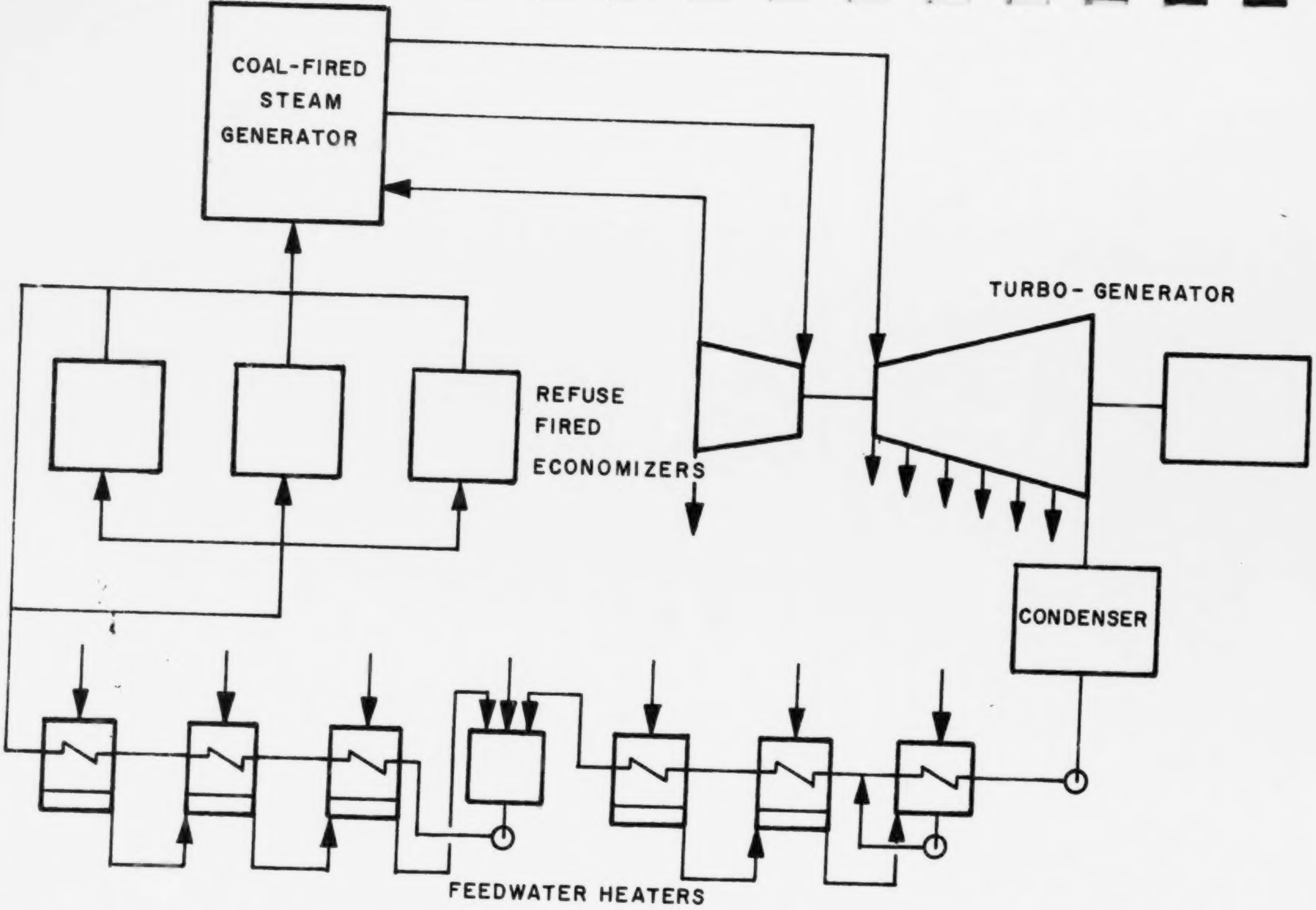
COAL-FIRED STEAM GENERATOR
TURBO- GENERATOR
REFUSE FIRED ECONOMIZERS
CONDENSER
FEEDWATER HEATERS

FIGURE III-50. STEAM CYCLE SCHEMATIC - SEPARATELY FIRED ECONOMIZER

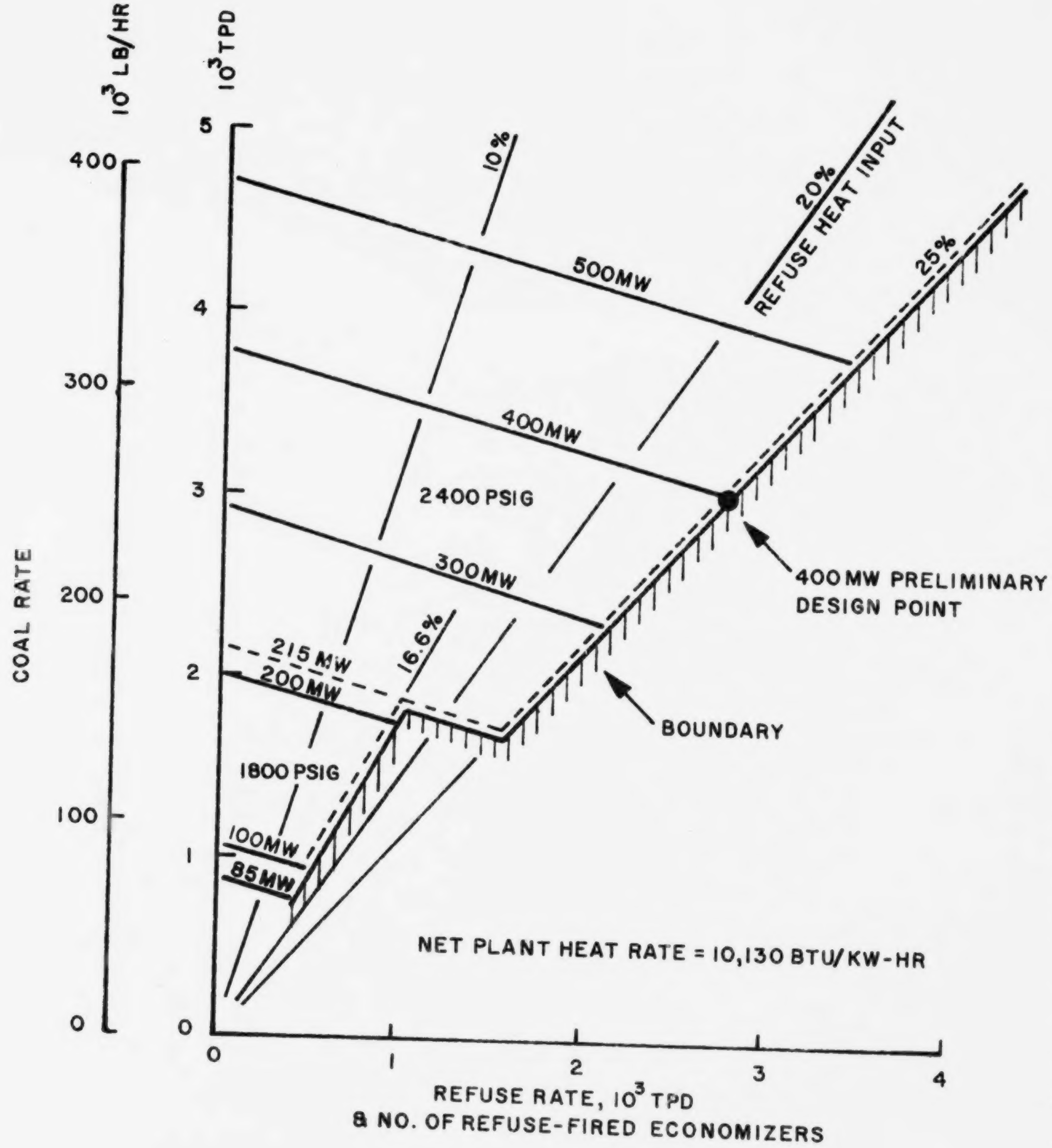

FIGURE III-51. PLANT FUEL REQUIREMENTS WITH SEPARATELY FIRED ECONOMIZERS

In designing a furnace chamber for combustion of any fuel, careful consideration must be given to the furnace exit-temperature. This temperature should be high enough to combust all volatile material, and, in the case of refuse, render the effluent gas as odorless as possible. The furnace exit-temperature should not exceed the ash fusion temperature, in that the subsequent convection surfaces would be subjected to fouling from molten ash. Based on domestic experience, such as that obtained with the unit at the U.S. Naval Station at Norfolk, Virginia, and that reflected in the TÜV performance reports, a furnace exit-temperature of 1800°F was selected.

The size of any given furnace is related to the furnace exit-temperature and heat absorption. Theoretical data supported by field experience are generally used in sizing the furnace for a specific fuel. In this case, the data were derived from both domestic and foreign experience.

Because of the relatively high ash content of refuse, vertical tube banks should be used wherever possible. In addition, tubular air heaters should be used in lieu of the more compact, regenerative type to minimize pluggage.

(3) Steam Generator

Pulverized coal would be fired in a dry-ash-bottom steam generator. In keeping with domestic practice for units of the present size, this would be a natural circulation type unit. The only difference between the present and a conventional unit design is that most of the economizer surface has been omitted.

It is claimed that in the Munich South (Unit No. 6) plant, the main consideration is a high degree of availability for power generation. If, for any reason, refuse delivery is stopped, full power generation capacity can be maintained by burning more fossil fuel, although at reduced efficiency. During the present system reanalysis, this claim was examined and found to be perplexing. In the present, related design, if refuse is not burned, the full load capacity is only slightly in excess of 300 MW as compared with the normal capacity of 400 MW. A more detailed explanation of the basic design difficulty follows.

On a weight basis, the feedwater flow in the parallel refuse-fired economizers is the same as that of the feedwater entering the steam generator and steam leaving the superheater. When refuse is not burned, the feedwater is brought to the steam generator at a lower temperature. For the same steam flow, therefore, the heat absorption in the steam generator must be increased to equal the heat normally absorbed by burning refuse. To offset this deficiency by merely firing more coal is not an adequate solution. In the design of the furnace chamber, the flue gas exit-temperature essentially determines heat absorption. If the furnace exit-temperature is excessively increased, fouling of convention sections may result and it would be difficult to control superheat temperature. In addition, the prevention of these unwanted effects must be observed over a range of loads, because as the load varies, the steam flow varies. In the present case, where refuse-firing is interrupted, the load of the steam generator will still vary but not the steam flow. The problem is analogous to that wherein a feedwater heater is lost from service. Typically, the solution to this operating situation is to reduce load, i. e., steam flow and power generation. Fuel flow is also decreased, but to a less than proportionate degree. The net effect is that cycle efficiency is lowered.

Several solutions were considered. Initially, some economizer surface was included in the fossil fuel steam generator. In the flue-gas temperature range involved, the location of this surface would be such that it would be rather ineffective under normal firing (i. e., refuse burning) conditions. On the other hand, if refuse were not burned, the flue gas temperatures over this surface would increase and more effective heat transfer would result, but it would be insufficient to overcome the thermal deficiency due to curtailed refuse burning. The addition of this surface does, however, represent a partial solution to the problem; it was therefore retained in the design. An additional benefit provided by this component is that the streams from the three economizers would be mixed therein so that flow and, more importantly, temperature fluctuations would be dampened before the fluids entered the steam drum.

To complete the resolution of the problem, it was further decided to include stand-by firing systems in the economizer units. Although the steam generator would be coal-fired, the stand-by equipment should preferably be for either oil or natural gas. It would be much more economical to do this than to expand the capacity of the (more expensive) coal handling system for a consumption rate that would probably be only infrequently encountered.

With the back-up firing system, it would be possible to operate the economizer units in either the combined or single fuel firing modes. In the event of a reduction in refuse availability, it would, however, be simpler to switch one unit at a time completely from refuse to fossil fuel, than to fire any or all of the three economizer units with mixed fuels.

Several other alternatives for compensating for possible refuse input reduction or interruption were considered and rejected. As suggested above, simply increasing the fuel rate in the steam generator would increase the furnace exit-temperature, thus necessitating the use of great amounts of spray cooling to bring the superheat and reheat temperatures to the desired control levels. Potential fouling of convective surfaces would also be a problem. Another solution would be to size the steam generator to accommodate an outage of all three economizer units. This would not only be quite costly but impractical. With all three economizers on line, the oversized steam generator would have to be turned down to the point that the final superheat outlet temperature would become unacceptable. Adopting a compromise furnace size still presented the disadvantages of the two choices of possible sizes (for normal operation and operation without economizers), while furnishing no major advantages.

Another solution would be to install a conventional economizer in the steam generator and use by-pass flues to control heat-input variations caused by shutdowns of the external economizer units. Such an arrangement was rejected as being excessively costly.

A final alternative that was considered was to increase the bleeds from the various turbine stages in order to raise the temperature of the feedwater entering the steam generator. This could be accomplished by incorporating additional heat-transfer surface in the feedwater heaters. This arrangement would reduce steam flow through the turbine and thus decrease the power output. Unfortunately, these bleeds are usually optimized for a given set of normal operating conditions. It is also likely that the optimization of a turbine-feedwater heating cycle for two sets of conditions would be uneconomical. In any case, it is difficult to achieve a better cycle efficiency by transferring the heat input of the Rankine cycle from regenerative heating to that derived from fuel combustion.

The foregoing discussion has perhaps been directed to a contingency situation that may suggest an overly cautious design approach. The refuse-fired economizers have actually been designed for an availability comparable to that of the coal-fired steam generator. The inherent multiplicity of three economizer units does offer an opportunity to repair any single economizer without suffering a severe power reduction. Furthermore, there would appear to be no greater chance of a decreased availability of refuse occurring than there would be of fossil fuel. Thus, in the preliminary design presented here, the fossil-fuel fired steam generator has been sized and cost-estimated on the basis of its normal fossil-fuel rate, which is approximately 300 MW. The stand-by arrangement wherein fossil-fuel firing equipment would be included in the refuse-fired economizers is considered to be an optional feature and, therefore, has not actually been included in either the design drawings or cost estimate.

It is perhaps appropriate at this point to compare the basic design considered here with that at Munich South, Unit No. 6. The fossil fuel steam generator at Munich South is a once-through (Benson) design, single (flue gas) pass, and of 124 MW capacity. A once-through unit does offer somewhat more liberty in furnace design than does a natural circulation unit, especially if the European "meandering" circuitry is employed (see Appendix B, Section III, A, 2). It is rare, however, to find a plant of under 400 MW capacity designed for once-through operation. In the United States, the break-even point between once-through and natural circulation units had been about 500 MW. In recent years, however, this has apparently increased to about 800 MW.

Concerning the single (flue gas) pass design of the Munich unit wherein both a superheater and reheater are involved, steam temperature is controlled by sprays installed in several locations. As suggested earlier, however, resorting to a great deal of spraying is not an economical practice for domestic applications.

(4) Performance Calculations

The calculation of the products of combustion discussed earlier (Table III-1) was repeated. This time, however, the calculations were expanded to include coal, as well as refuse, and to derive values for a range of excess air levels. The latter was done to permit the evaluation of system characteristics at lower steam generation loads. Generally, at lower loads, it is necessary to increase excess air to maintain safe flue-gas temperatures in the convection passes.

These data are presented in Table III-15. It will be noted that at 50% excess air, the refuse-derived values are slightly lower than shown in Table III-1. This is largely because the correction for unburnt carbon had been omitted in the earlier derivation as being of minor importance. Other small differences are also involved. The specific humidity of the combustion air, for example, has been increased to 0.013 lbs of water per pound of dry air.

The ultimate analyses employed were, of course, identical with those shown in Section III, B for refuse and coal. The theoretical oxygen requirement used in calculating Table III-15 was 0.718 lb/lb of refuse and 2.101 lb/lb of coal. The unburnt carbon was assumed to be 1.85% and 0.66% for the refuse and coal, respectively.

Efficiency calculations for coal firing (18% excess air) at various flue gas exit-temperatures are shown in Table III-16. The procedure used is in accordance with the ASME Power Test Code, and was explained earlier in Table III-2. It will be noted that the radiation loss has been isolated from the subtotal in Table III-16. This was done to facilitate the use of the table with different sized units; radiation loss is the only factor that varies with capacity. Coal firing efficiency is also plotted in Figure III-52 as a function of flue gas temperature. It can be seen that a decrease of 40°F in the flue gas exit temperature results in a gain in efficiency of 1%.

TABLE III-15

PRODUCTS OF COMBUSTION AT VARIOUS EXCESS AIR LEVELS

	EXCESS AIR %								
	Refuse						Coal		
	0	25	50[1]	75	100	150	18[1]	23	40
I. Quantities, lb/lb of Fuel									
Combustion Air (dry)	3.10	3.87	4.65	5.42	6.20	7.75	10.71	11.17	12.71
CO_2 Formed	0.913						2.42		
SO_2 Formed	0.002						0.74		
N_2 in Flue Gas	2.39	2.98	3.58	4.17	4.77	5.96	8.24	8.59	9.77
Dry Flue Gas	3.30	4.08	4.85	5.63	6.40	7.95	11.12	11.57	13.11
H_2O in Comb. Air	0.04	0.05	0.06	0.07	0.08	0.10	0.14	0.15	0.17
H_2O in Fuel	0.271						0.085		
H_2O formed by Comb.	0.304						0.420		
Total Flue Gas H_2O	0.615	0.625	0.635	0.645	0.655	0.676	0.645	0.651	0.672
(wt-% in Wet FG)	(15.7)	(13.3)	(11.6)	(10.3)	(9.3)	(7.8)	(5.5)	(5.3)	(4.9)
Wet Flue Gas	3.92	4.72	5.49	6.27	7.06	8.63	11.76	12.22	13.78
II. Flue Gas Composition, Vol-%									
CO_2 (2)	14.8	12.4	10.7	9.4	8.3	6.8	13.9	13.3	11.8
SO_2 (2)	0.02	0.02	0.02	0.01	0.01	0.01	0.29	0.28	0.25
H_2O (2)	0.24	0.21	0.18	0.16	0.15	0.12	0.09	0.09	0.08
O_2 (3)	0	4.2	7.0	9.0	10.5	12.6	3.3	4.0	6.1
III. Flue Gas Average Molecular Weight	28.03	28.15	28.23	28.29	28.34	28.41	29.65	29.62	29.51

---

(1) Design Value
(2) Wet Flue Gas Basis
(3) Dry Flue Gas Basis

TABLE III-16

EFFICIENCY OF COAL-FIRED STEAM GENERATOR

(Duty = 2,635 x 10^6 Btu/hr)

Temperature of Gas Leaving Air Heater, °F	250	300	325	350	400	450	500
Heat Losses, %							
Dry Gas	3.78	4.89	5.45	6.00	7.12	8.22	9.33
Hydrogen and Moisture in Fuel	4.52	4.61	4.66	4.70	4.80	4.89	4.98
Moisture in Air	0.09	0.12	0.13	0.15	0.17	0.20	0.23
Unburned Combustible	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Unaccounted For & Mfrs Margin	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Subtotal	10.55	11.78	12.40	13.01	14.25	15.47	16.70
Radiation	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Total Losses, %	10.73	11.96	12.58	13.19	14.43	15.65	16.88
Efficiency, %	89.27	88.04	87.42	86.81	85.57	84.35	83.12

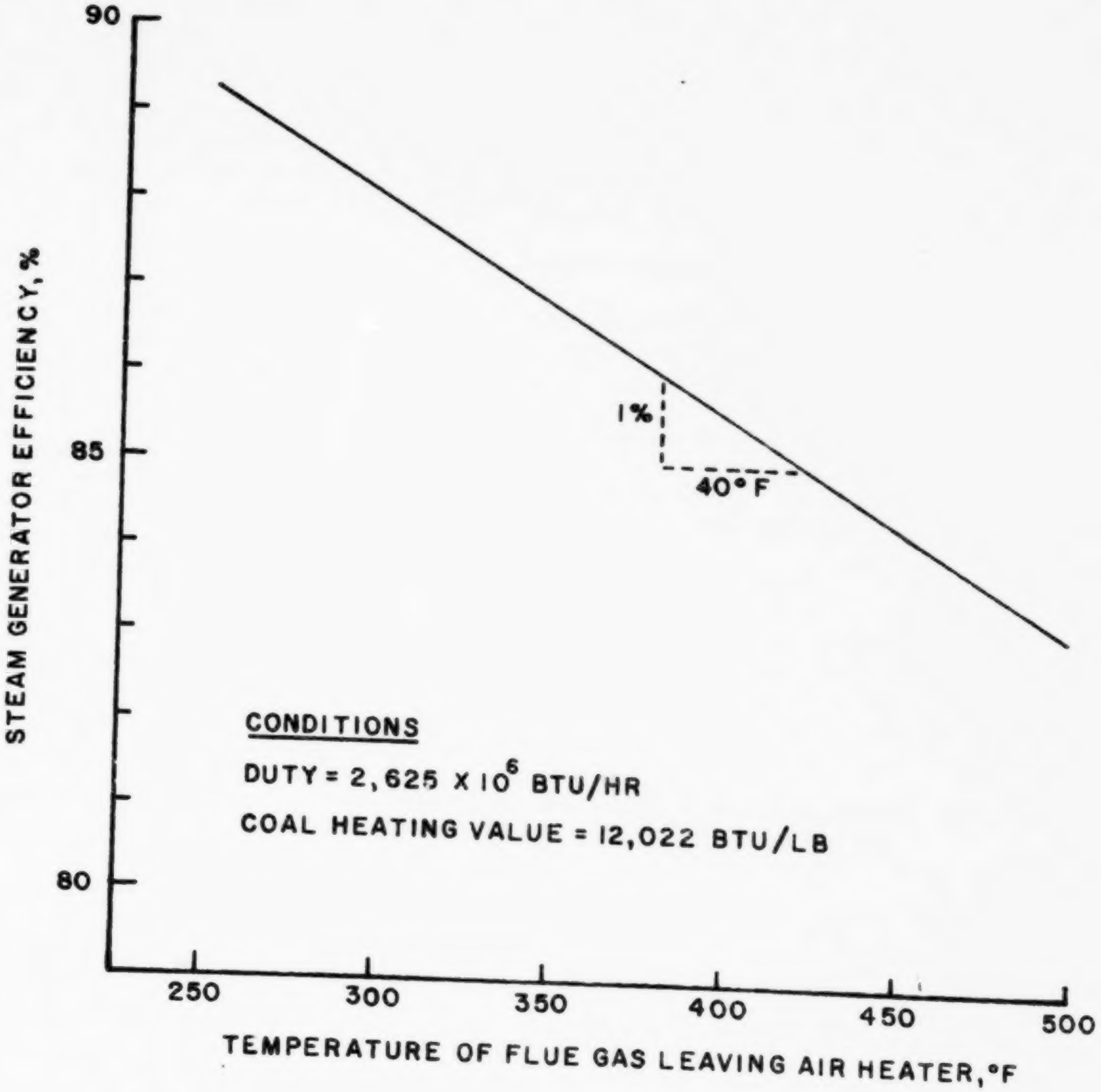

FIGURE III-52. EFFECT OF FLUE GAS EXIT TEMPERATURE ON STEAM GENERATOR EFFICIENCY

The efficiency for refuse firing is given in Tables III-17, -18, and -19. The calculations were done at two different flue gas exit-temperatures for various excess air levels and also at various flue gas temperatures for the design (50%) excess air level. In presenting the data, the moisture in the fuel is reported separately from the water developed by the combustion of hydrogen in the fuel because of the relatively large magnitude of each of these losses. The heat losses associated with the moisture in the combustion air, unburned combustibles, and sensible heat in the ash have been combined because each is relatively small and none are appreciably influenced by the exit-temperature of the flue gas or the level of excess air. The radiation loss is treated as in the previous table. The data in Tables III-17, -18, and -19 have been combined in Figure III-53, which, on the basis of flue gas exit-temperature and excess air level, thus constitutes a rather complete map of efficiencies.

(5) Design Details

The design of the refuse-fired economizers and fossil fuel fired steam generator were based on the standardized procedures of the Foster Wheeler Corp. This included the use of computerized calculations. Cost estimates for material, shop fabrication and field erection were provided by Foster Wheeler's commercial departments. The results of this effort, namely the drawings and cost estimates, generally agreed closely enough with those developed for the candidate evaluation stage that an iterative analysis of the systems proved unnecessary.

The design, as developed, is quite amenable to load variations when the relative quantities of refuse and coal, i.e., 25% and 75% heat input respectively, are held constant. However, as the load varies, especially below 75% of full power generation, a variation in refuse rates between 0 and 25% of the heat input is also permissable. The summary of the duties for the three economizers and the single steam generator is as follows:

THERMAL FACTORS FOR SEPARATELY
FIRED ECONOMIZER PLANT (400 MW)

System	Fuel	Duty, 10^6 Btu/hr	Efficiency, %	Heat Input 10^6 Btu/hr	Heat Input %
Economizers	Refuse	687	66.22	1037.3	25.6
Steam Gen.	Coal	2633	87.42	3014.2	74.4
Combined		3320	81.93	4051.5	100.0

Each refuse-fired economizer would burn 930 tpd of fuel to establish a maximum plant rate of 2790 tpd of refuse. The steam generator would burn coal at a rate of 3008 tpd. The net plant heat rate would be 10,130 Btu/kw-hr.

TABLE III-17

EFFICIENCY OF REFUSE-FIRED ECONOMIZER AT VARIOUS EXCESS AIR LEVELS

(Flue Gas Exit Temp. = 575°F; Duty per Unit = 228 x 10^6 Btu/hr)

Excess Air, %	0	25	50	75	100	150
Heat Losses, %						
Dry Gas	8.79	10.87	12.92	15.00	17.04	21.17
Moisture in Fuel	7.74	7.74	7.74	7.74	7.74	7.74
Moisture From Hydrogen	8.74	8.74	8.74	8.74	8.74	8.74
Misc Small Losses*	2.50	2.50	2.50	2.50	2.50	2.50
Unaccounted For	0.50	0.50	0.50	0.50	0.50	0.50
Mfrs Margin	1.00	1.00	1.00	1.00	1.00	1.00
Subtotal	29.27	31.35	33.40	35.48	37.52	41.65
Radiation	0.38	0.38	0.38	0.38	0.38	0.38
Total Losses, %	29.65	31.73	33.78	35.86	37.90	42.03
Efficiency, %	70.35	68.27	66.22	64.14	62.10	57.97

---

*Moisture in air, unburned combustibles, and sensible heat in ash

TABLE III-18

EFFICIENCY OF REFUSE-FIRED ECONOMIZER AT VARIOUS EXCESS AIR LEVELS

(Flue Gas Exit Temp. = 450°F; Duty per Unit = 228 x 10^6 Btu/hr)

Excess Air, %	0	25	50	75	100	150
Heat Losses, %						
Dry Gas	6.57	8.12	9.67	11.17	12.74	15.83
Moisture in Fuel	7.38	7.38	7.38	7.38	7.38	7.38
Moisture From Hydrogen	8.34	8.34	8.34	8.34	8.34	8.34
Misc Small Losses*	2.50	2.50	2.50	2.50	2.50	2.50
Unaccounted For	0.50	0.50	0.50	0.50	0.50	0.50
Mfrs Margin	1.00	1.00	1.00	1.00	1.00	1.00
Subtotal	26.29	27.84	29.39	30.89	32.46	35.55
Radiation	0.38	0.38	0.38	0.38	0.38	0.38
Total Losses, %	26.67	28.22	29.77	31.27	32.84	35.93
Efficiency, %	73.33	71.78	70.23	68.73	67.16	64.07

---

*Moisture in air, unburned combustibles, and sensible heat in ash

TABLE III-19

EFFICIENCY OF REFUSE-FIRED ECONOMIZER AT VARIOUS FLUE GAS EXIT-TEMPERATURES

(Excess Air = 50%; Duty per Unit = 228 x 10^6 Btu/hr)

Gas Temp. Leaving Air Heater, %	300	350	400	450	500	550	575	600
Heat Losses, %								
Dry Gas	5.74	7.00	8.34	9.66	10.94	12.26	12.92	13.57
Moisture in Fuel	6.96	7.10	7.24	7.40	7.52	7.66	7.74	7.80
Moisture From Hydrogen	7.85	8.01	8.17	8.33	8.48	8.64	8.74	8.80
Misc Small Losses*	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Unaccounted For	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Mfrs Margin	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Subtotal	24.55	26.11	27.75	29.39	30.94	32.56	33.40	34.17
Radiation	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Total Losses, %	24.93	26.49	28.13	29.77	31.32	32.94	33.78	34.55
Efficiency, %	75.07	73.51	71.87	70.23	68.68	67.06	66.22	65.45

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*Moisture in air, unburned combustibles, and sensible heat in ash

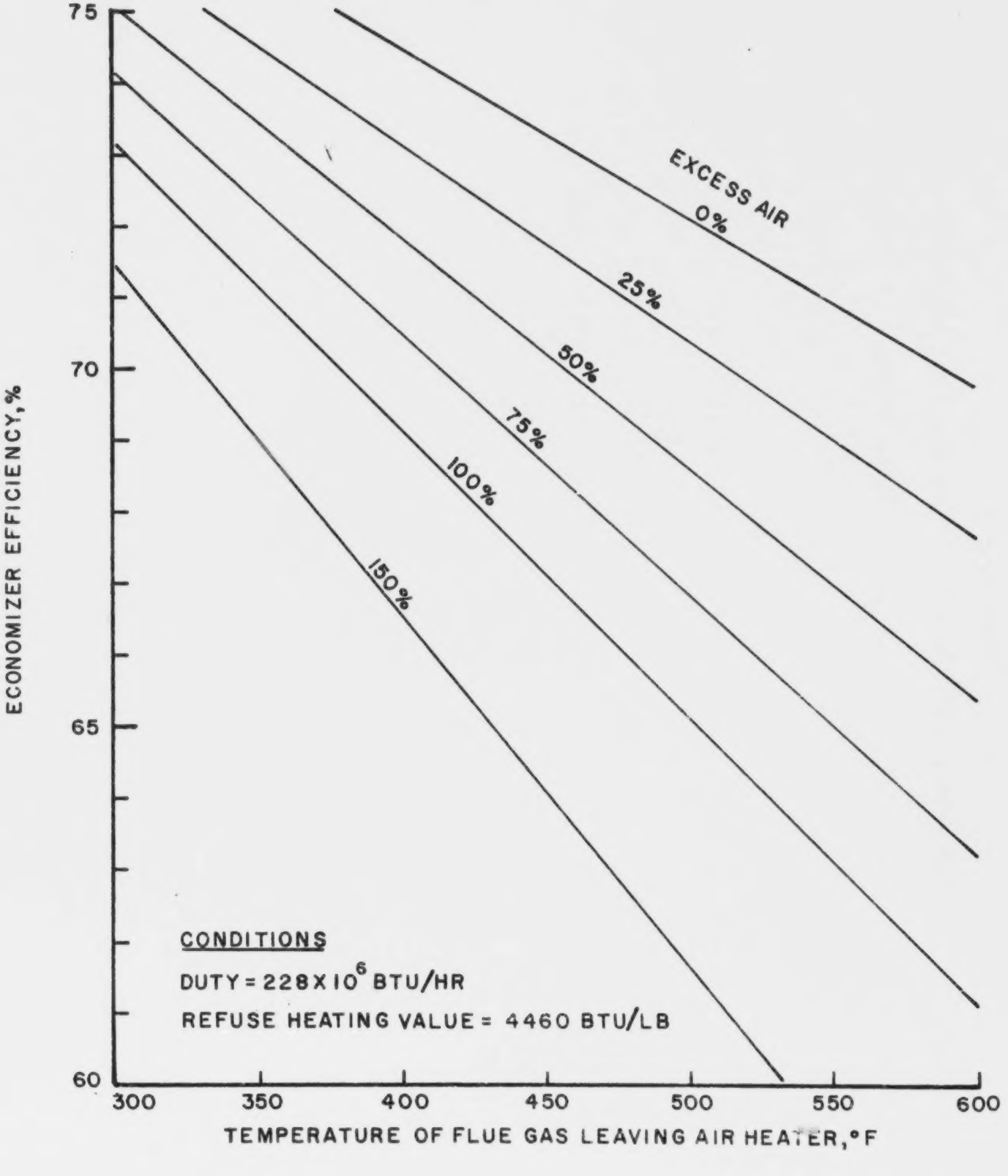


FIGURE III-53. EFFECT OF FLUE GAS EXIT TEMPERATURE ON EFFICIENCY OF REFUSE-FIRED ECONOMIZEI

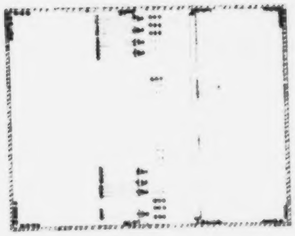
(a) Economizer

A drawing of the economizer unit is given in Figure III-54 and the water circuitry is shown schematically in Figure III-55. The summary performance data in presented in Table III-20.

Refuse would be fed through a vertical, water-cooled chute and burn on a thick fuel bed. The grate incorporated should furnish both agitation and tumbling to the fuel mass to insure good burnout. High velocity, secondary air nozzles would be provided in the front and rear walls to promote complete combustion of volatile gases and particles rising from the fuel bed. The configuration of the combustion zone was influenced by both domestic and more recent European experience (Refs. 50 and 104). All walls and the roof would be of welded tube-and-fin construction. Tube banks, especially in areas of relatively high gas temperatures, would be arrayed vertically. Horizontal tube banks would be of bare tube design in all cases. A tubular air heater, in which the flue gas would be directed downward inside the tubes, would be used because of its ease of cleaning. Ash hoppers would be appropriately located to remove ash where tube banks might act as ash deflectors.

Feedwater would be flowed in a single continuous (once-through) path. Flue gas would be directed in a two-pass arrangement and be discharged into a dust collector located at grade level. Air, preheated to 316°F, would be delivered as underfire air. This temperature was selected as being compatible with the cast iron grate. Approximately 25% of the preheated air would be sent through a booster fan and delivered as high velocity secondary air.

The water wall panels would consist of 3-in. OD tubes spaced on 3-3/4-in. centers with fins continuously welded between tubes. Because of the all-metal construction, slag adhesion should be minimal. Gas-borne, molten slag-particles would be cooled upon contacting the tube or fin and thus tend to shed from the surface. The solid walls would be impervious to gas penetration, so that a costly refractory setting would be unnecessary. In the design of the rear wall of the furnace, a "nose" has been incorporated at the furnace exit to insure good gas distribution. This wall would also form a three-row deep slag screen. The screen would be arrayed with a longitudinal spacing of 5-in. and a transverse spacing of 11-1/4-in. The boiler bank design consists of 2-1/2-in. OD tubes, three rows deep on 7-1/2-in. spacing, and thirty-one elements across on 11-in. spacing, arrayed in an in-line configuration. The horizontal tubes are 3-1/2-in. OD tubes, which would also be in-line on 5 x 5-in. centers. The loops would be supported from the front and rear panel-walls of the second pass. Ample space has been provided in the design for sootblowers. The air heater would consist of 1500 12 ft-long, 2-1/2-in. OD tubes arranged in a 4-1/2-in. spaced, in-line pattern. On the air-side, the gas flow would follow a three-pass, cross-flow path.



SECTION "A-A"

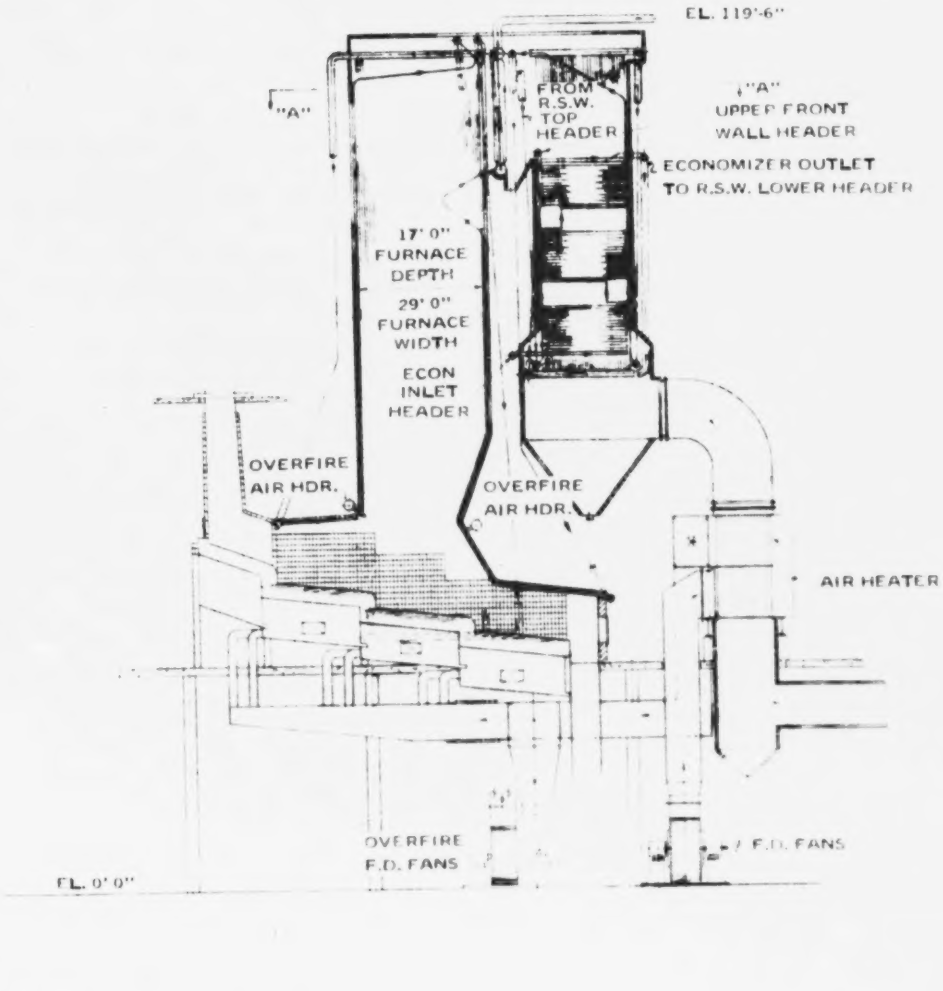

EL. 119'-6"
"A"
"A"
UPPER FRONT
WALL HEADER
FROM
R.S.W.
TOP
HEADER
ECONOMIZER OUTLET
TO R.S.W. LOWER HEADER
17' 0"
FURNACE
DEPTH
29' 0"
FURNACE
WIDTH
ECON
INLET
HEADER
OVERFIRE
AIR HDR.
OVERFIRE
AIR HDR.
AIR HEATER
OVERFIRE
F.D. FANS
F.D. FANS
EL. 0' 0"

FIGURE III-54. SEPARATELY FIRED ECONOMIZER

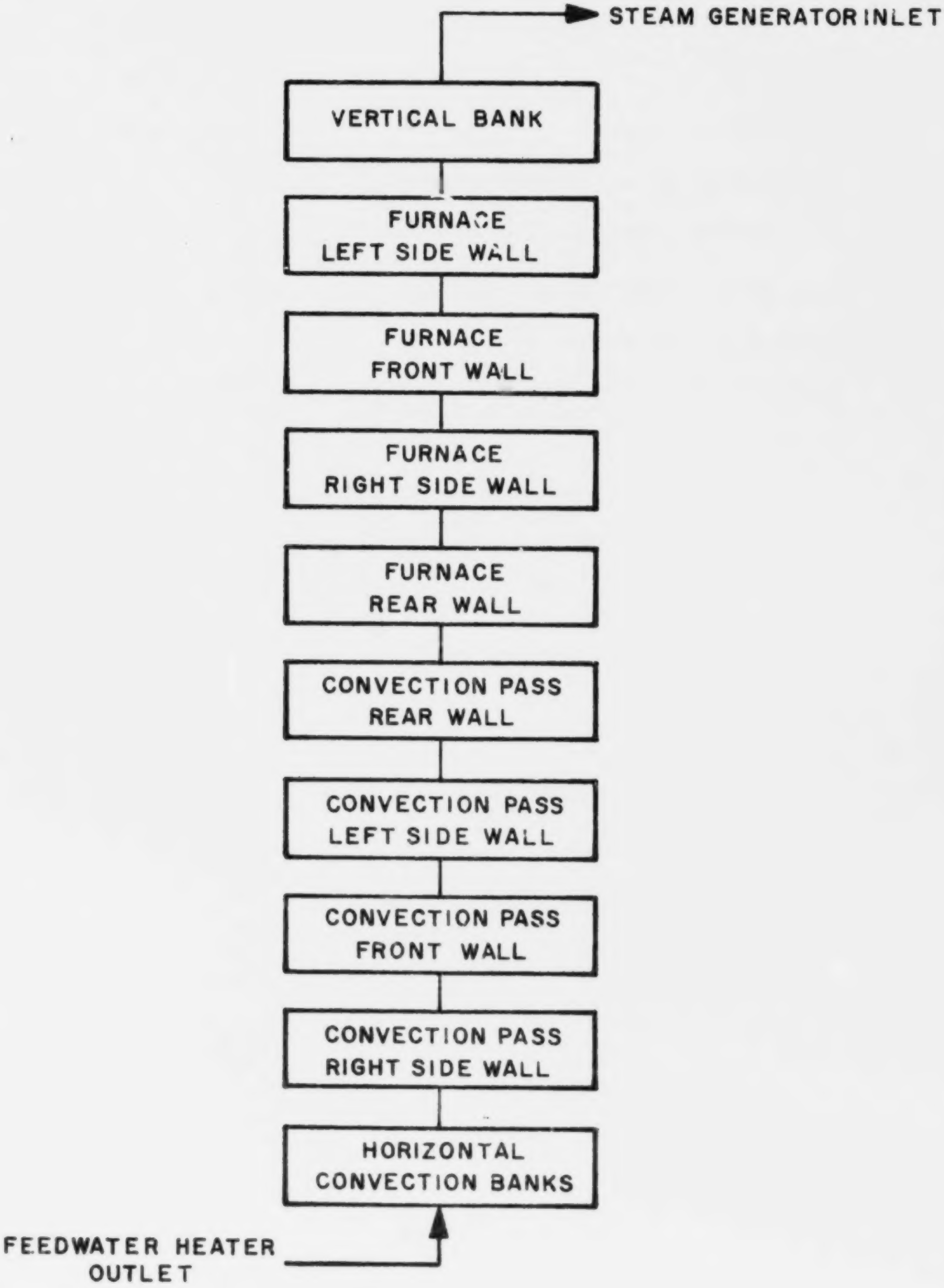

STEAM GENERATOR INLET
VERTICAL BANK
FURNACE LEFT SIDE WALL
FURNACE FRONT WALL
FURNACE RIGHT SIDE WALL
FURNACE REAR WALL
CONVECTION PASS REAR WALL
CONVECTION PASS LEFT SIDE WALL
CONVECTION PASS FRONT WALL
CONVECTION PASS RIGHT SIDE WALL
HORIZONTAL CONVECTION BANKS
FEEDWATER HEATER OUTLET

FIGURE III-55. FLOW DIAGRAM - REFUSE FIRED ECONOMIZER

TABLE III-20

SUMMARY PERFORMANCE OF REFUSE-FIRED ECONOMIZER

Refuse fired, tpd	930
Combustion air input (50% excess), 10^3 lb/hr	360
Wet flue gas produced, 10^3 lb/hr	425
Economizer efficiency, %	66.2
Feedwater output, 10^3 lb/hr	933
Pressure at feedwater outlet, psig	2600
Temperature, °F	
Feedwater outlet	657
Feed entering unit	470
Air entering unit	80
Air leaving air heater	316
Flue gas leaving furnace	1800
Flue gas entering air heater	766
Flue gas leaving air heater	575

(b) Steam Generator

The drawing of the coal-fired steam generator is shown in Figure III-56 and the water/steam circuitry is shown schematically in Figure III-57. The summary performance data is given in Table III-21. In most respects, the design of this unit is conventional. The main difference is in the design layout of the heating surface. The heat absorbed in this unit would be largely accomplished by the superheater and reheater because of the use of the refuse-fired economizers. As mentioned earlier, however, some economizer surface would be included in the steam generator. The small section of economizer surface shown in Figure III-56 is situated under the convection superheater. In conventional units a small section of total economizer surface is usually located under the convection superheater, and the remainder is located to follow the parallel pass.

The furnace would have panel walls consisting of 3-in. OD tubes on 3-3/4-in. centers with continuous fins welded between the tubes. In the upper furnace, five "wing" division walls would comprise a radiant superheater incorporating 2-in. OD tangent tubes. A parallel pass arrangement would be used in the second pass. Superheat temperature would be controlled by the firing rate and by spraying. Reheat temperature would be controlled by regulating the gas-flow with dampers.

(6) Cost Estimates

Following the development of preliminary designs just discussed, detailed costs were derived for the optimum system. This was done according to the procedure described in Section III, C, 1. A notable variation, however, was that the costs for FPC Code No. 312 (Boiler Plant Equipment) were generated by commercial estimators of the Foster Wheeler Corporation.

From the design calculations and drawings, a complete materials list was first prepared. The units were then designated for shop fabrication vs outside production scheduling. Shop costs included material, labor, and overhead. Included in overall costs were engineering and normal overhead expenses and profit. Field erection costs were derived using a straight time basis and an average labor rate of $10.00/hr. Freight charges were based on an average location.

The results of this more detailed costing are shown in Table III-22. In comparing these costs with those presented in Table III-13 of the cost model, it can be seen that a significant reduction in refuse disposal cost has resulted. To a large extent, this resulted from a design decision made during the optimization study.

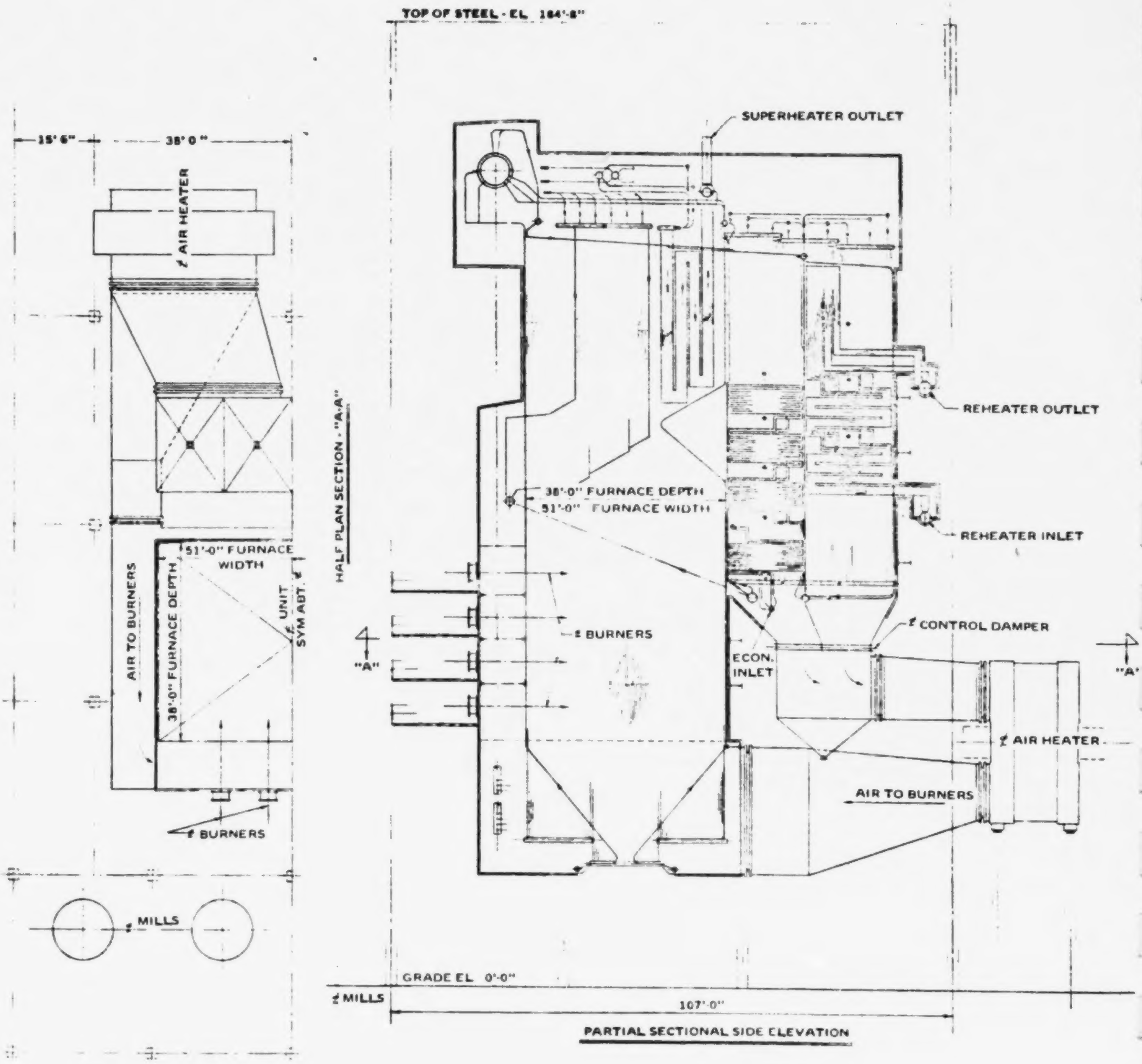

TOP OF STEEL - EL 184'-8"
15' 6"
38' 0"
℄ AIR HEATER
SUPERHEATER OUTLET
REHEATER OUTLET
REHEATER INLET
HALF PLAN SECTION - "A-A"
38'-0" FURNACE DEPTH
51'-0" FURNACE WIDTH
51'-0" FURNACE WIDTH
AIR TO BURNERS
38'-0" FURNACE DEPTH
℄ UNIT SYM ABT. ℄
℄ BURNERS
"A"
ECON. INLET
℄ CONTROL DAMPER
"A"
℄ AIR HEATER
AIR TO BURNERS
℄ BURNERS
℄ MILLS
GRADE EL 0'-0"
℄ MILLS
107'-0"
PARTIAL SECTIONAL SIDE ELEVATION

FIGURE III-56. COAL FIRED STEAM GENERATOR

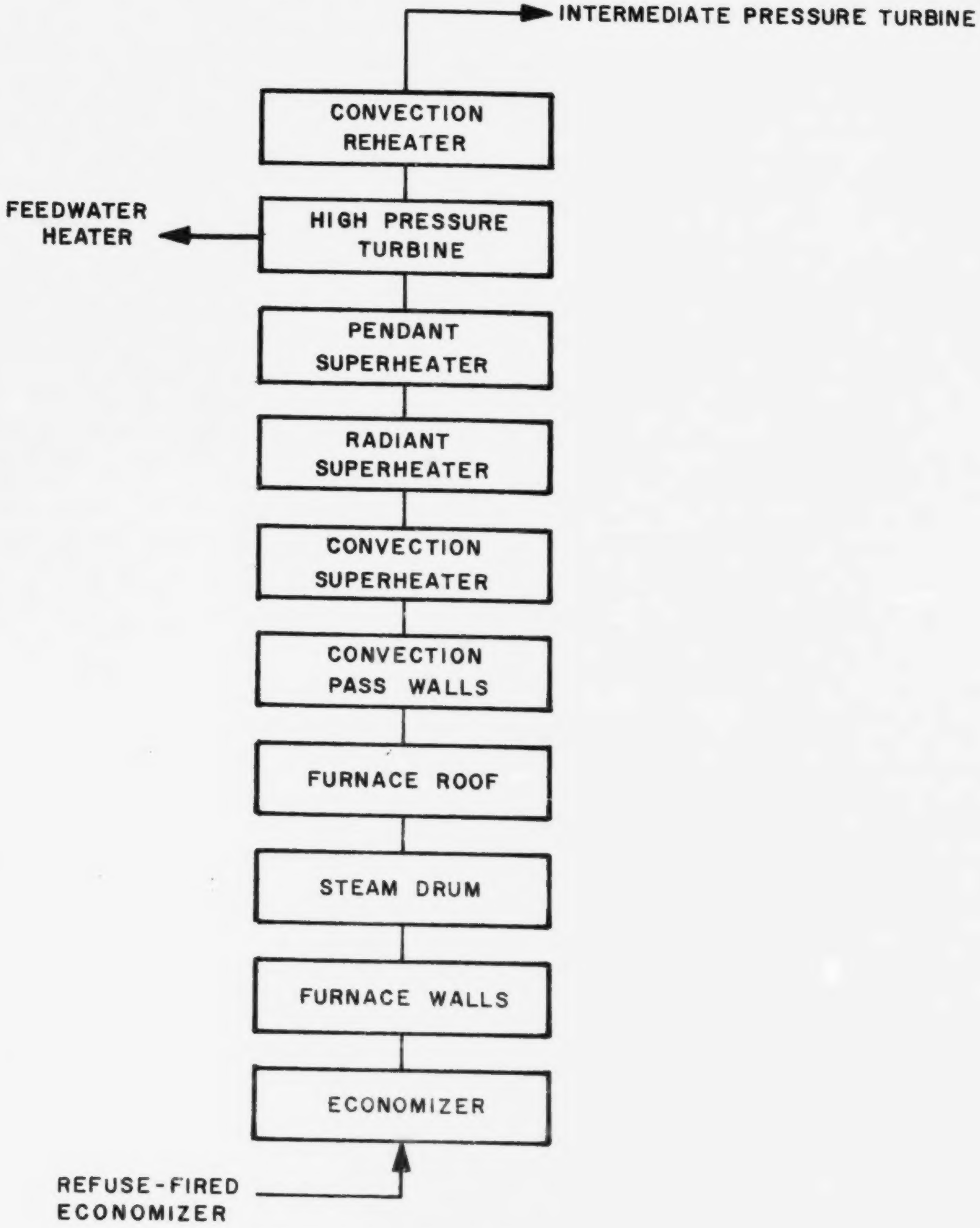

INTERMEDIATE PRESSURE TURBINE
CONVECTION REHEATER
FEEDWATER HEATER
HIGH PRESSURE TURBINE
PENDANT SUPERHEATER
RADIANT SUPERHEATER
CONVECTION SUPERHEATER
CONVECTION PASS WALLS
FURNACE ROOF
STEAM DRUM
FURNACE WALLS
ECONOMIZER
REFUSE-FIRED ECONOMIZER

FIGURE III-57. FLOW DIAGRAM - COAL FIRED STEAM GENERATOR

TABLE III-21

SUMMARY PERFORMANCE OF COAL-FIRED STEAM GENERATOR WITH EXTERNAL, REFUSE-FIRED ECONOMIZERS

Coal fired, tpd	3008
Combustion air input (18% excess), 10^3 lb/hr	2740
Wet flue gas produced, 10^3 lb/hr	3004
Steam produced, 10^3 lb/hr	2800
Reheat steam, 10^3 lb/hr	2464
No. of coal-mills operating	4
Steam generator efficiency, %	87.4
Pressure, psig	
Superheater outlet	2520
Boiler drum	2640
Reheater inlet	577
Reheater outlet	518
Temperature, °F	
Superheater outlet steam	1000
Reheater inlet steam	640
Reheater outlet steam	1000
Feedwater entering unit	657
Air entering unit	80
Air leaving air heater	764
Gas leaving furnace	2260
Flue gas entering air heater	825
Flue gas leaving air heater	325

TABLE III-22

REVISED COSTS FOR THE SEPARATELY FIRED ECONOMIZER PLANT

CAPITAL COSTS

FPC Codes	Description	Cost, 10^6 \$
310	Land and Land Rights	0.69
311	Structures and Improvements	5.47
312	Boiler Plant Equipment	31.72
314	Turbine-Generator Equipment	13.75
315	Accessory Electrical Equipment	2.87
316	Misc. Power Plant Equipment	0.59
	Air Pollution Control Equipment	4.04
	Waste Handling Equipment	1.81
	Engineering and Inspection	2.44
	Total Capital Cost	63.38

ANNUAL COSTS

Annual Capital Cost, 10^6 \$ (Effective annualization rate, 14.6 percent)	9.25
Water Cost, 10^6 \$	0.01
Operating Labor, 10^6 \$	0.62
Maintenance, 10^6 \$	1.73
Coal Cost, 10^6 \$	6.76
Residue Disposal, 10^6 \$	0.36
Total Annual Costs, 10^6 \$	18.73
Annual Credit for Power Generated, 10^6 \$	18.76
Quantity of Waste Burned, 10^3 ton/yr	815
Disposal Cost, \$/ton	-0.04
Transportation Cost (3.50 Mile Haul Radius), \$/ton	1.64
Total Net Disposal Cost, \$/ton	1.60

Originally, the Case 3 coal-fired steam generator design had been dimensioned so that this boiler would be capable of assuming the entire plant load in the event of an outage of all three refuse-fired economizers. As pointed out earlier in the present discussion, anticipating such a contingency can be accomplished in a more cost-effective manner (see Section III, C, 2, b, (3)). The steam generator design was accordingly reduced to the size required for normal firing conditions (75% heat input from coal).

The net result of this iteration has been to render the Separately Fired Economizer an even more attractive system for which minimal application risk is evident.

c. Arch Furnace with Separate Superheater

(1) Preliminary Engineering Technical Factors

As in the original Case 10 conception of this design, feedwater would be taken from the last stage feedwater heater and be evaporated and superheated at a temperature of 750°F in an arch-type furnace. Further superheating to 1000°F and reheating would be accomplished in a separate, coal-fired superheater.

In considering this design in further detail, a problem came to light concerning the location of reheat tube surface. If these tubes are located in an area of high gas temperature, tube damage or failure may occur during start-up, when no steam is being returned to them from the turbine. In conventional boilers, reheat surface is always installed in locations where the tubes can be protected from excessive temperatures, especially during the initial phases of start-up. For the case of the partial superheat and reheat unit considered here, this was not possible. It was therefore concluded that separate units for the reheat and final superheat duty would have to be provided. Figure III-58 diagrams the basic arrangement that was observed in developing the preliminary design of the present system.

An alternate configuration was also seriously considered. This would have consisted of a twin-furnace arrangement for the coal-fired superheat/reheat function. This design would have represented a substantial cost savings over the three-unit configuration actually chosen. The alternate design approach, although potentially quite practical, was not taken because of concern over possible risk factors that would not be encountered in the three-unit system.

Based on a refuse input-rate limit of 2000 tpd for grateless furnaces, a map of fuel requirements and steam cycle options was developed and is shown in Figure III-59. The 60% refuse rate has again been imposed as an arbitrary boundary. In this case, however, the rate is

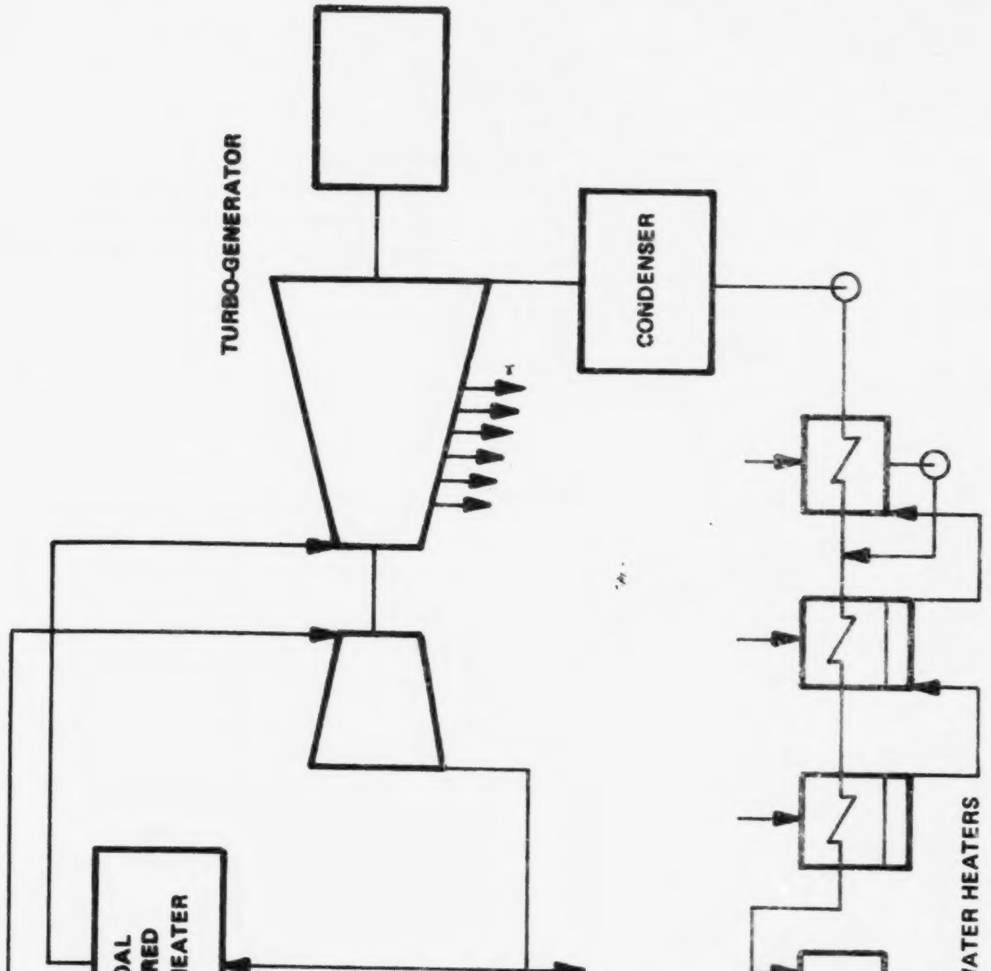

TURBO-GENERATOR
CONDENSER
COAL FIRED REHEATER
COAL FIRED SUPERHEATER
REFUSE AND COAL FIRED STEAM GENERATOR
FEEDWATER HEATERS

FIGURE III-58. STEAM CYCLE SCHEMATIC - ARCH FURNACE PLANT

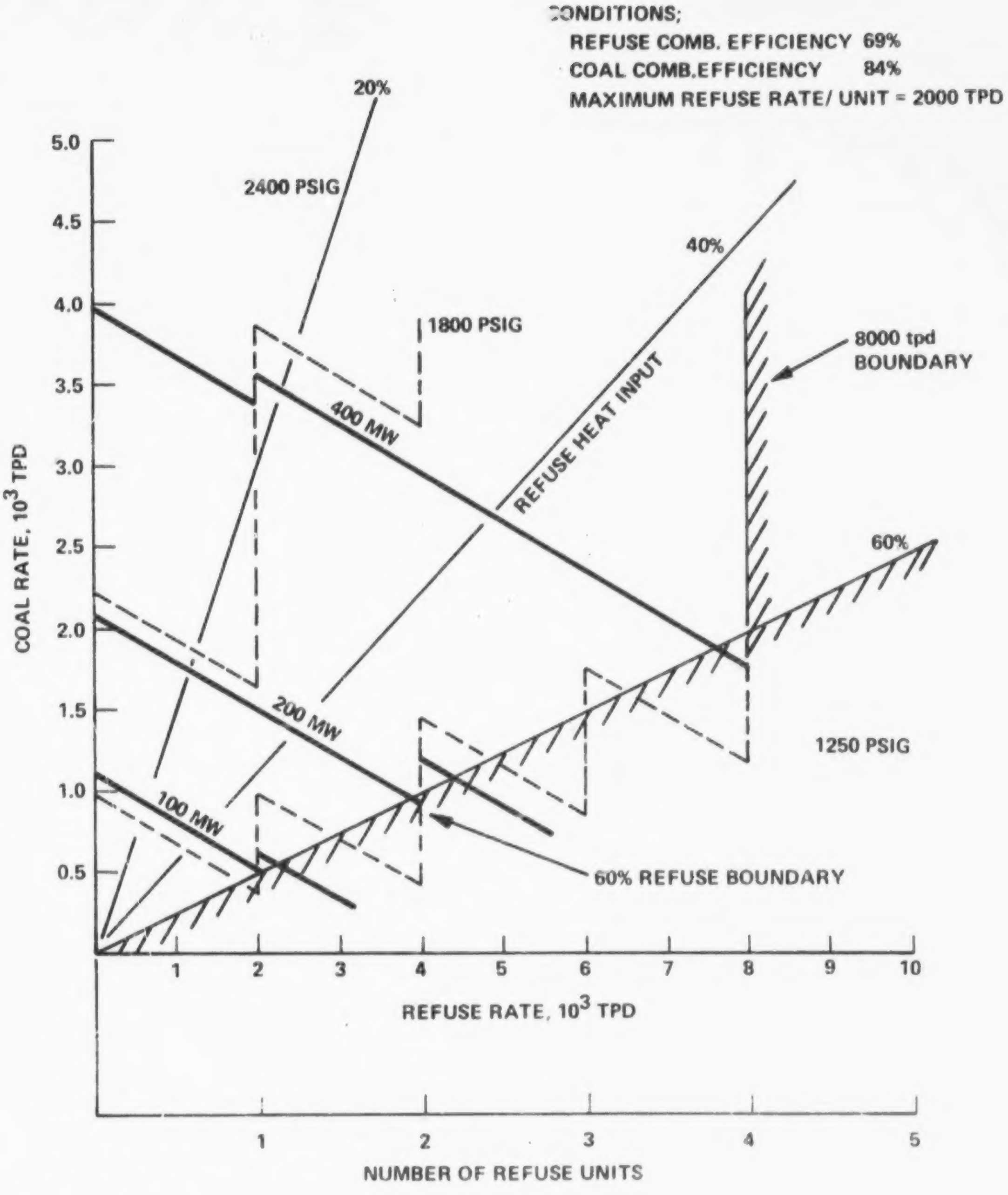


FIGURE III-59. FUEL REQUIREMENTS FOR COMBINED FIRING (BLENDED FLUE GASES) AT HIGHER REFUSE RATE

not predicated on concern for steam-flow variations. The determining factor is that refuse rates exceeding 60% would necessitate a 1250 psig, non-reheat cycle and the use of multiple steam generators and turbines. A suspension-fired steam generator is not likely to experience the steam flow variations that have been experienced with grate-stoked units.

In terms of the arch furnace itself, the refuse rate was arbitrarily set to allow some (20%) coal firing and thus the promotion of more stable combustion conditions. This corresponded to overall plant refuse heat input fractions of 59.8 and 56.4% for the 1800 and 2400 psig cycles, respectively. These points are shown in Figure III-60, which presents fuel requirements in terms of both the plant and the combined fired arch furnace. Also shown are possibilities for firing 75% and 100% refuse in the arch furnace. The resultant curves exceed the plant refuse-rate of 60%, but this is merely illustrative. As can be seen, the firing of 100% refuse in the arch furnace would lead to impractical steam conditions and an unwanted multiplicity of units. In fact, 80% refuse-firing in the arch furnace is marginal. Because of this, the heat input into the arch furnace was reduced to 75%, which corresponds to overall plant refuse-fractions of 55.9 and 52.7% for the 1800 and 2400 psig cycles, respectively. The size of the plant was set at 100 MW, as determined by the cost modeling.

In the system thus far described, the combined-fired arch furnace and the coal-fired superheater would operate so that the flue gas leaving the air heaters would be at about 450°F. This is based on dust collector requirements. In the coal-fired superheater unit, the temperature of the gas leaving the tube banks of the boiler would certainly be higher than in a conventional boiler, because the latter would be equipped with an economizer and the former would have a higher inlet feedwater-temperature. Some of the increase in sensible heat could be returned to the system by way of the air heater, but not to the extent typical of conventional plants. Thus, somewhat lower efficiencies must be expected.

The combustion calculations for the present system are essentially the same as those developed for the system discussed in the preceding section (Separately Fired Economizer). The steam generator efficiencies were also derived on the same basis, except that the radiation loss value was changed because of the difference in the plant capacities of the two systems. The following efficiency data for the arch furnace arrangement are thus based on Tables III-16 and -18 shown earlier, with the exception of the radiation loss.

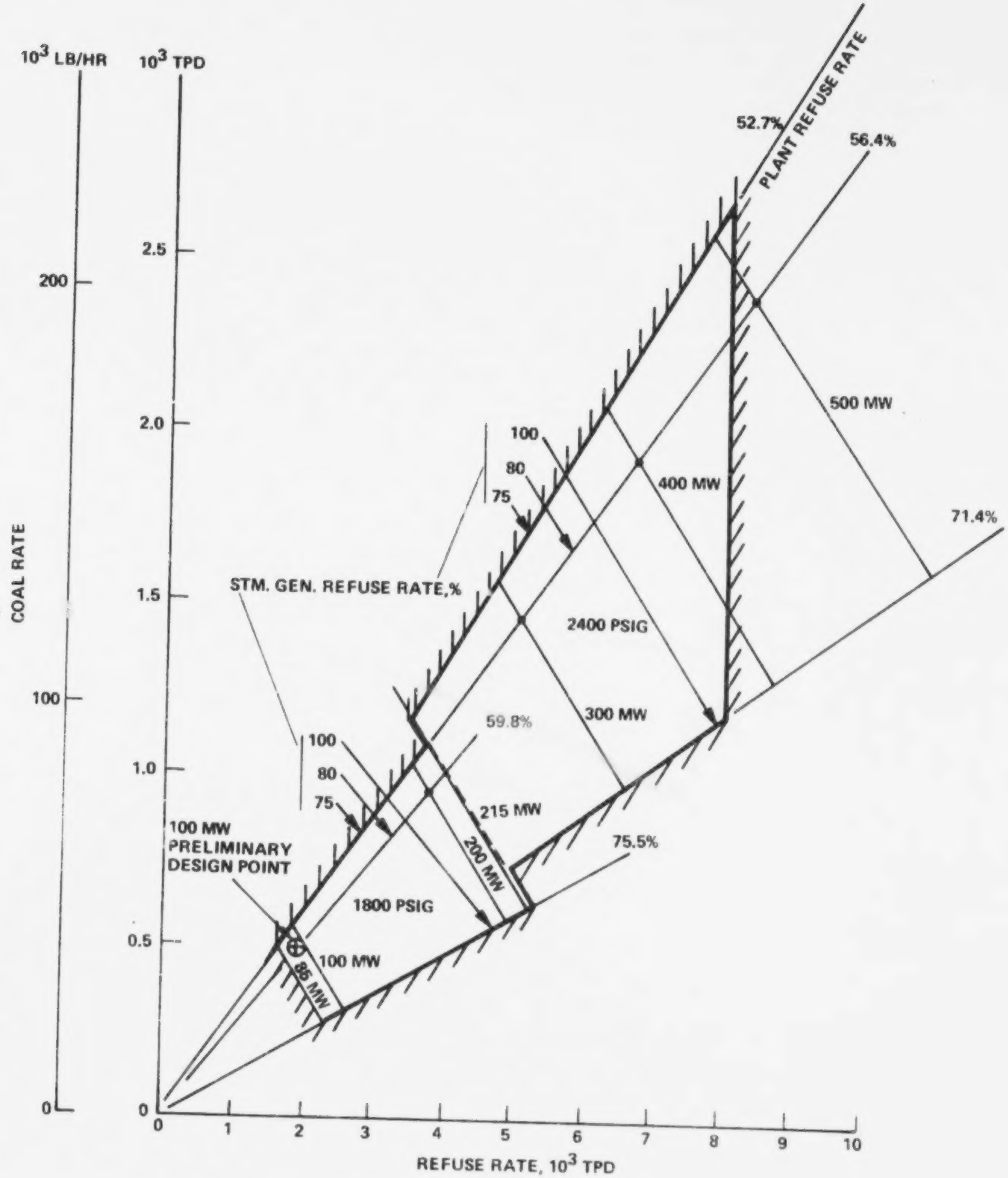


FIGURE III-60. FUEL REQUIREMENTS FOR ARCH FURNACE PLANT

EFFICIENCY OF ARCH FURNACE WITH SEPARATE COAL-FIRED SUPERHEATER AND REHEATER

	Arch Furnace	Superheater	Reheater
Radiation loss, %	0.26	0.40	0.40
All other losses, %	26.61	15.47	15.47
Total, %	26.87	15.87	15.87
Efficiency, %	73.13	84.13	84.13

Note: Flue gas exit-temperature = 450°F (all units); excess air = 50% (refuse), and 18% (coal).

(2) Design Details

The system, as thus far presented, would be quite amenable to load variations when the fuel proportions are held constant. At any given load, however, a plant refuse rate as low as 10% could also be accommodated.

The summary of the respective duties for the steam generator, superheater, and reheater is as follows:

THERMAL FACTORS FOR ARCH FURNACE WITH SEPARATELY FIRED SUPERHEATER AND REHEATER

Unit	Fuel	Duty 10^6 Btu/hr	Eff. %	Heat Input 10^6 Btu/hr	Heat Input %
Steam Generator	Refuse (80%) & Coal (20%)	666	73.16	910	74.3
Superheater	Coal	138	84.13	164	13.4
Reheater	Coal	126	84.13	150	12.3
Plant	-	930	75.98	1224	100.00

The arch furnace and thus the plant refuse rate would be 1960 tpd. The arch furnace would also burn 182 tpd of coal, the superheater 164 tpd, and the reheater 150 tpd, for a plant coal rate of 496 tpd. The net plant heat rate would be 12,240 Btu/kw-hr. The fuel requirement point for this 100 MW plant can be seen on Figure III-60.

(a) Arch Furnace Steam Generator

The arch furnace steam generator is shown in Figure III-61, the schematic of the water circuitry in Figure III-62, and the

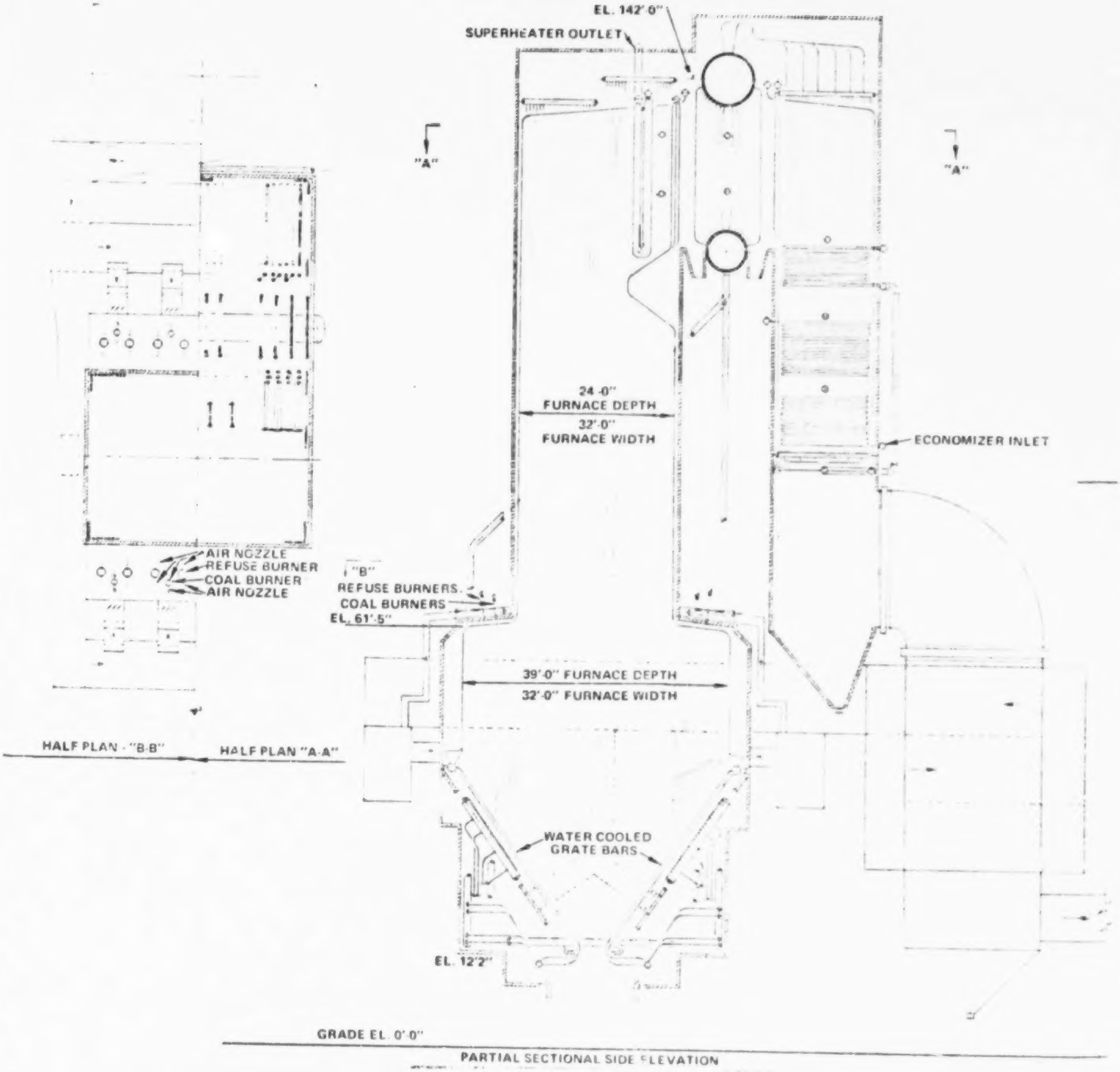

EL. 142'-0"
SUPERHEATER OUTLET
"A"
"A"
24'-0" FURNACE DEPTH
32'-0" FURNACE WIDTH
ECONOMIZER INLET
AIR NOZZLE
REFUSE BURNER
COAL BURNER
AIR NOZZLE
"B"
REFUSE BURNERS
COAL BURNERS
EL. 61'-5"
39'-0" FURNACE DEPTH
32'-0" FURNACE WIDTH
HALF PLAN - "B-B"
HALF PLAN "A-A"
WATER COOLED GRATE BARS
EL. 12'2"
GRADE EL. 0'-0"
PARTIAL SECTIONAL SIDE ELEVATION

FIGURE III-61. COMBINED-FIRED ARCH FURNACE FOR 100 MW PLANT

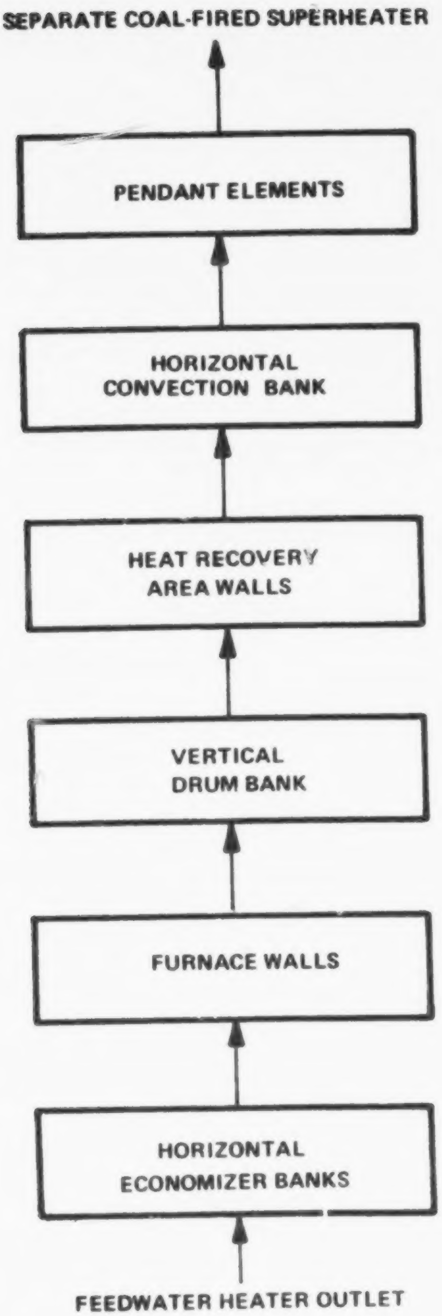

SEPARATE COAL-FIRED SUPERHEATER
PENDANT ELEMENTS
HORIZONTAL CONVECTION BANK
HEAT RECOVERY AREA WALLS
VERTICAL DRUM BANK
FURNACE WALLS
HORIZONTAL ECONOMIZER BANKS
FEEDWATER HEATER OUTLET

FIGURE III-62. FLOW DIAGRAM - ARCH FURNACE STEAM GENERATOR

summary performance in Table III-23. The furnace shape chosen for this steam generator is similar to that of an anthracite coal burning furnace. The arch section of a typical anthracite furnace that has proven to be effective in the past is shown in Figure III-63. The furnace design used for the present steam generator differs from that shown in the arrangement of the hopper area. Water-cooled grate bars would be installed on the sides of the hopper to collect and burn any refuse particles that might fall into the hopper before being completely combusted. A set of detailed drawings (Figures III-32 and -33) of this type of arrangement was presented in connection with Modification No. 5 of the retrofit units. This same construction would be used for the present furnace.

It should be mentioned at this point that this particular design treatment may prove unnecessarily conservative. If the furnace fired satisfactorily without grate bars on the hopper walls, a significant cost savings would be realized by omitting this structure. This is essentially the course of action now planned in an EPA-supported demonstration program based on the design proposed in Reference 41. This ongoing retrofit operation will result in a system similar to that outlined for Modification No. 5, except that no grate surface of any kind will be installed.

In the arch furnace, there would be three zones where secondary air would be admitted into the lower furnace. These would be the lower furnace arch, the lower furnace front and rear walls, and the hopper. Each would have separate windboxes and separately controlled air supplies. The proportion of air introduced into any one of these zones would be adjustable, within certain limits, to vary the flow patterns within the furnace. It is anticipated that some experimentation will be necessary to determine the secondary air distribution pattern that will afford optimum suspension and burnout of the fuel.

Both shredded refuse and pulverized coal would be transported by pneumatic systems and injected into the furnace at the arch. The fuel would mix with secondary air in the lower furnace and most of the combustion should take place in that zone. The upper part of the furnace would constitute an area where combustion could go to completion. The pendant superheater, rear-wall screen tubes, and vertical drum bank would be set on wide spacings to avoid fouling. The economizer tube banks would consist of 2-in. O.D. bare tubes arranged in an in-line pattern on 4-1/4-in. centers across the unit.

The steam-side design is that of a conventional natural circulation circuit. Water would be fed from the economizer outlet to the upper drum. The relatively cool water would then flow into the downcomers and pass into the furnace walls. The hopper tubes would not be of panel-wall construction because they should be situated in a staggered double-row arrangement to accommodate the water-cooled grate bars. The furnace-side walls and the front and rear walls above the arches would consist

TABLE III-23

SUMMARY PERFORMANCE OF ARCH FURNACE STEAM GENERATOR

Refuse fired, tpd	1960
Coal fired, tpd	182
Number of coal mills in operation	2
Combustion air input (47.3% excess), 10^3 lb/hr	943
Wet flue gas produced, 10^3 lb/hr	1099
Steam output, 10^3 lb/hr	759
Unit efficiency, %	73.2
Pressure, psig	
Boiler	1975
Superheater outlet	1940
Temperature, °F	
Superheater outlet steam	750
Feed entering unit	440
Feed leaving economizer	594
Air entering unit	80
Air leaving air heater	426
Flue gas leaving furnace	1800
Flue gas entering air heater	723
Flue gas leaving air heater	450

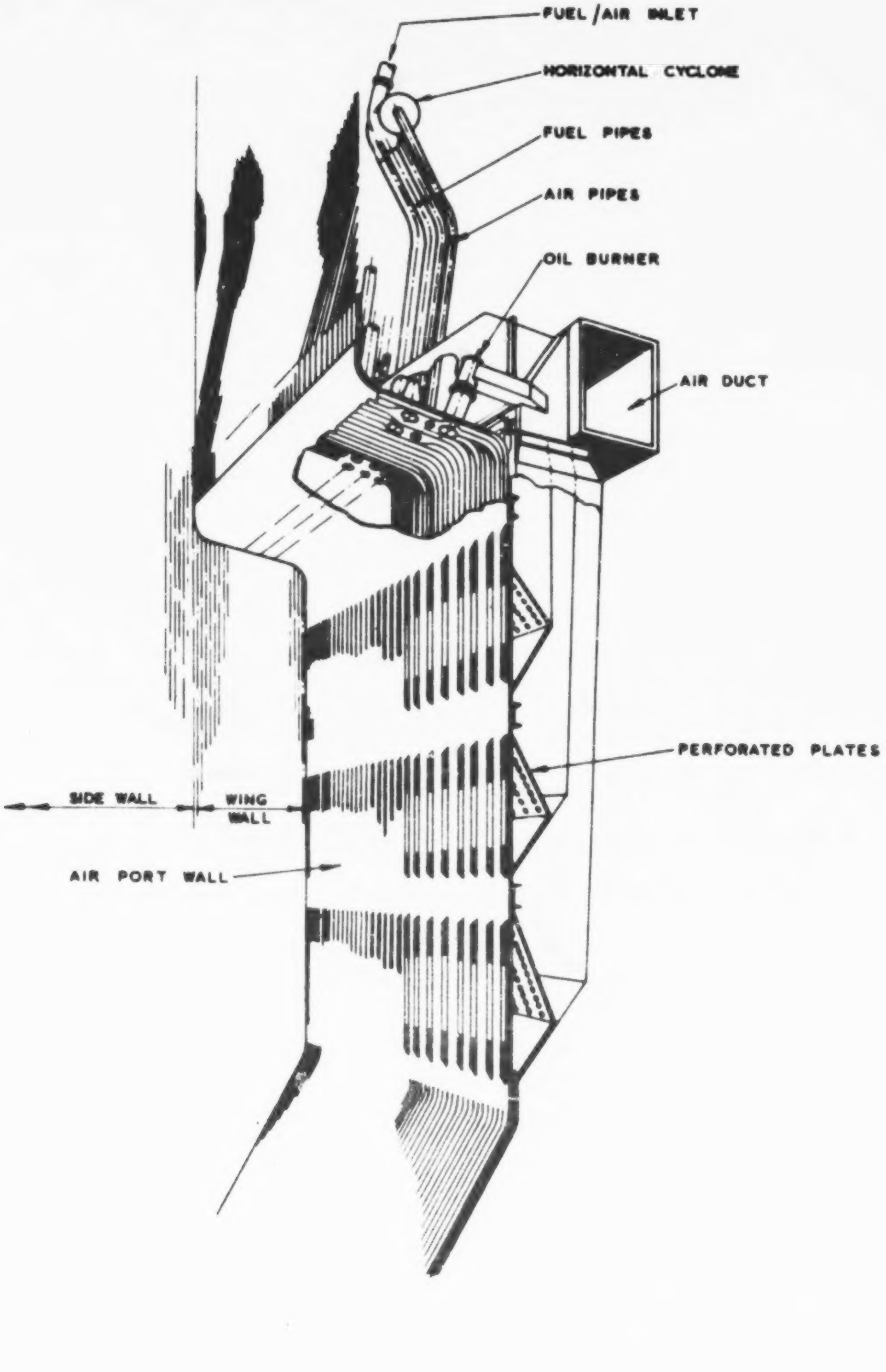

FUEL/AIR INLET
HORIZONTAL CYCLONE
FUEL PIPES
AIR PIPES
OIL BURNER
AIR DUCT
PERFORATED PLATES
SIDE WALL
WING WALL
AIR PORT WALL

FIGURE III-63. DETAIL OF ARCH SECTION OF ANTHRACITE FURNACE

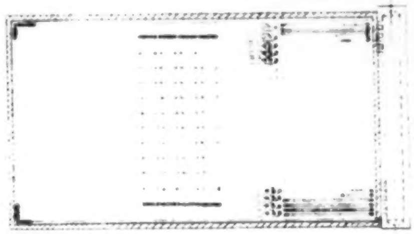
of panel-walls having 3-in. O.D. tubes spaced on 3-3/4-in. centers. The upper furnace wall headers would feed into the upper drum, where the dry steam would be separated and fed down the walls in the heat recovery zone. The walls in the latter zone would also be of panel-wall construction, with 1-3/4-in. O.D. tubes spaced on 4-1/3-in. centers. At the bottom of the heat recovery area, the steam would be collected in headers and transferred to the convection superheater, which is located at the top of the heat recovery pass. The convection superheater would have a two-tube, loop-in-loop pattern. This type of a tube bank is economically preferred over a single tube arrangement. The 2-1/4-in. O.D. tubes in this bank would be situated on 5-3/8-in. centers across the unit. The steam leaving the convection superheater would then be transferred to the pendant superheater. There would be eight pendant superheater-elements spaced across the unit. Each of the elements would consist of five 2-1/4-in. O.D. tubes. The steam temperature leaving the pendant superheater would be 750°F.

(b) Superheater

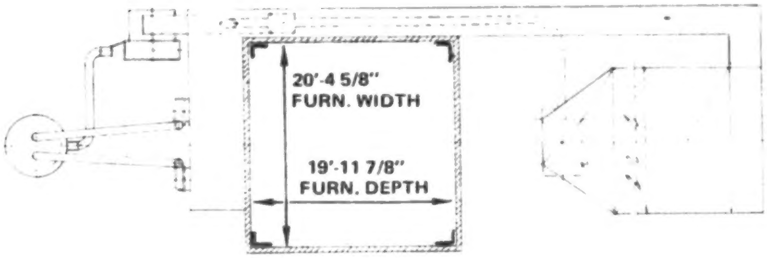
The design of the coal-fired superheater unit is shown in Figure III-64, the schematic of the steam circuitry in Figure III-65, and the summary performance in Table III-24. The duty of the unit being small, the furnace exit-temperature was set at 1600°F in order to achieve sufficient furnace volume. This lower than normal furnace exit-temperature did not pose any particular design problem. The only other part of the gas-side design that is somewhat unconventional is the incorporation of a tubular air heater. As discussed previously, the gas leaving the boiler will have a relatively high temperature because no economizer surface would be provided. High gas temperatures within the air heater could cause damage to the tube metal. Although regenerative air heaters are less expensive, it was felt that a tubular air heater with one section (upper 10 ft) constructed of alloy steels would be the preferred design. The air heater would be made up of 1500 2-1/2-in. O.D. x 30-ft long tubes.

The 750°F steam leaving the refuse-fired steam generator would first be fed to the heat recovery zone tube-banks. These banks would be composed of 2-in. O.D. tubes spaced on 4-3/4-in. centers. Each row would have a two-tube, loop arrangement. At the top of the convection superheater bank, the tubes of the bank would be bent to form a tube wall, which would be connected in a header at the top of the unit. From there, steam would flow through the roof and down the front wall tubes. The remaining furnace walls, consisting of 2-1/4-in. O.D. tubes, would then be fed in succession. Panel-wall construction would not be used in the furnace walls because in long, steam-carrying tubes the variations in temperature can cause an uneven expansion of the tube and fin assembly.

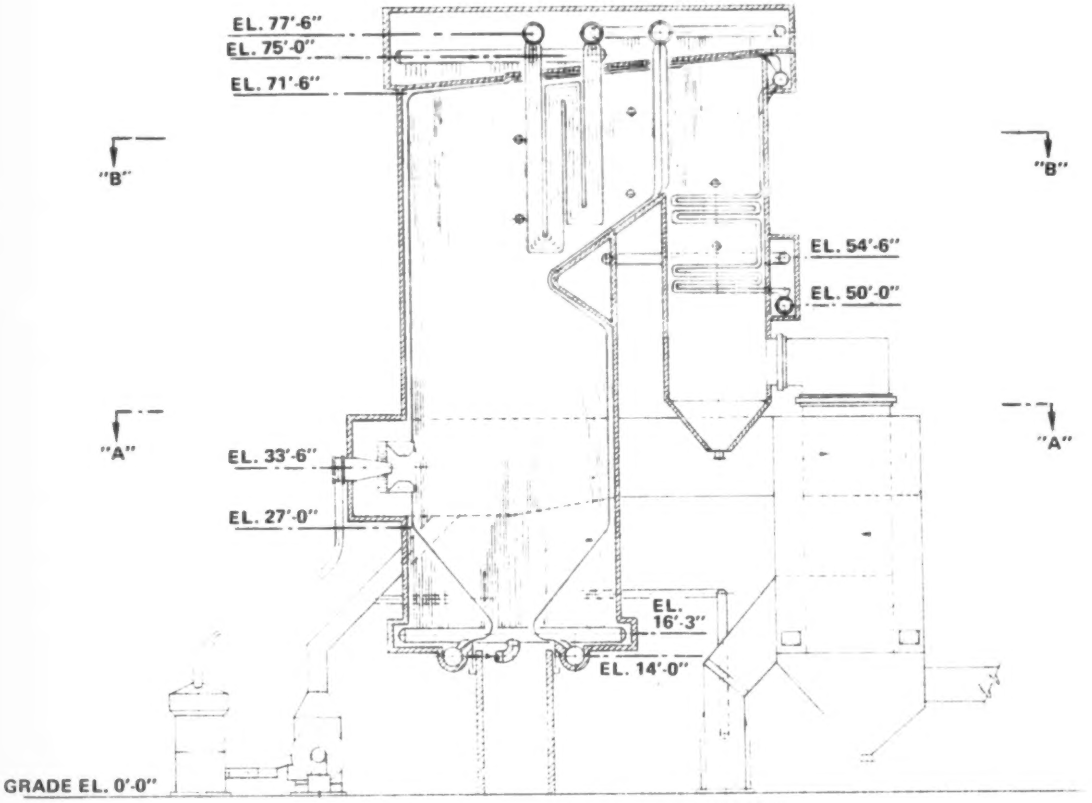
After the steam leaves the last furnace wall, it would be fed through the side walls above the heat recovery area. These tubes would also be 2-1/4 in. O.D. The last tube surface in the steam circuit would be the pendant superheater, which would consist of twelve elements spaced transversely across the unit, each element containing five 2-in. O.D. tubes.



PLAN AT SECT. "B-B"


20'-4 5/8"
FURN. WIDTH
19'-11 7/8"
FURN. DEPTH

PLAN AT SECT. "A-A"


EL. 77'-6"
EL. 75'-0"
EL. 71'-6"
"B"
"B"
EL. 54'-6"
EL. 50'-0"
"A"
"A"
EL. 33'-6"
EL. 27'-0"
EL. 16'-3"
EL. 14'-0"
GRADE EL. 0'-0"

PARTIAL SECTIONAL SIDE ELEVATION

FIGURE III-64. COAL-FIRED SUPERHEATER FOR 100 MW ARCH FURNACE PLANT

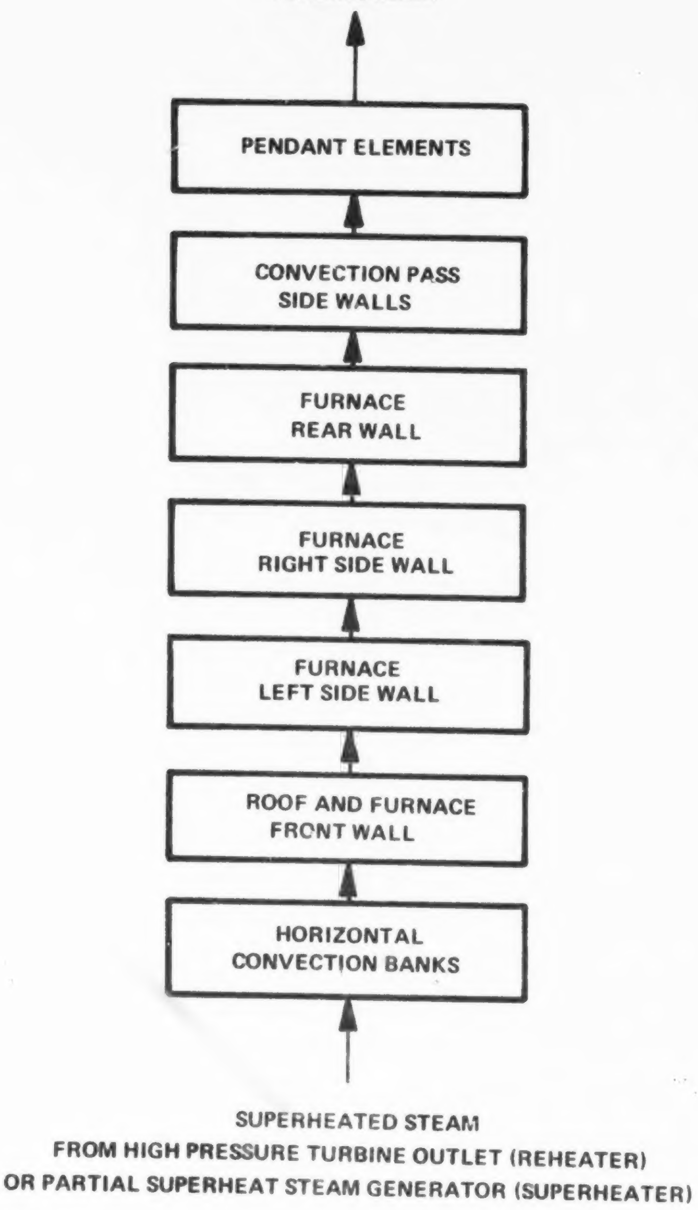

TURBINE INLET
PENDANT ELEMENTS
CONVECTION PASS SIDE WALLS
FURNACE REAR WALL
FURNACE RIGHT SIDE WALL
FURNACE LEFT SIDE WALL
ROOF AND FURNACE FRONT WALL
HORIZONTAL CONVECTION BANKS
SUPERHEATED STEAM
FROM HIGH PRESSURE TURBINE OUTLET (REHEATER)
OR PARTIAL SUPERHEAT STEAM GENERATOR (SUPERHEATER)

FIGURE III-65. FLOW DIAGRAM - SEPARATE SUPERHEATER AND REHEATER OF ARCH FURNACE PLANT

TABLE III-24

SUMMARY PERFORMANCE OF COAL-FIRED SUPERHEATER AND REHEATER (ARCH FURNACE SYSTEM)

	Superheater	Reheater
Coal fired, tpd	164	150
Number of mills in operation	1	1
Combustion air input (18% excess), 10^3 lb/hr	149	136
Wet flue gas produced, 10^3 lb/hr	164	149
Steam superheated, 10^3 lb/hr	759	668
Unit efficiency, %	84.1	84.1
Pressure, psig		
Unit outlet	1880	490
Steam entering unit	1940	520
Temperature, °F		
Unit outlet steam	1000	1000
Steam entering unit	750	660
Air entering unit	80	80
Air leaving air heater	614	572
Flue gas leaving furnace	1600	1600
Flue gas entering air heater	900	862
Flue gas leaving air heater	450	450

(c) Reheater Unit

The gas side design of the reheater unit would be essentially the same as that of the superheater. The heat inputs and steam temperatures would be almost identical, so that similar volume and surface requirements would be involved. The design of the coal-fired reheater is shown in Figure III-66, and the summary performance above in Table III-24. The steam circuitry would be the same as that shown earlier in Figure III-65.

The steam side design of the reheater and superheater units would differ because the pressures of the two units would not be the same (490 vs 1880 psig, respectively). Thus the tube thickness or diameter (or both) would have to be selected to accommodate each case. Another difference in the steam side design would be the number of tubes that could be fed in parallel. At a lower pressure, the increased specific volume of the steam permits the in-parallel operation of a greater number of tubes. This can be seen in the design of the convection and pendant banks of the reheat unit. The convection bank would be comprised of 201 (4-in. O.D.) tubes spaced on 4-3/4-in. centers. Each row would have a three-tube, loop-in-loop arrangement. The pendant elements would also be 2-1/4-in. O.D., with 10 tubes per element. The tubes in the tube-walls of the reheat unit would have the same outside diameter and spacing as those of the superheater, although the tube thicknesses would be different.

(3) Cost Estimates

The iterative cost analysis of the arch furnace plant was handled in the same manner as the Separately Fired Economizer and also reacted to the effect of decisions made in the detailed engineering analysis. In the present case, however, disposal costs were increased rather than reduced.

A summary of the cost data is presented in Table III-25. A comparison of the disposal cost with those given in the Cost Model will show a significant increase due to the FPC Code No. 312 entry change.

The resulting increase in total net disposal cost substantially reduced the edge previously held by the Arch Furnace plant over the other syspension-fired systems[*]. In fact, it would now appear to be less cost-effective than Case 7 (Stoker-Spreader). Although a detailed design analysis of the latter system could not be undertaken, a review was made to detect any possible design change requirements or other factors that might significantly alter the original capital cost estimates. It was

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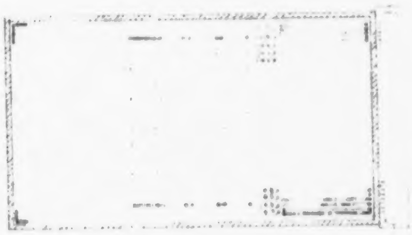
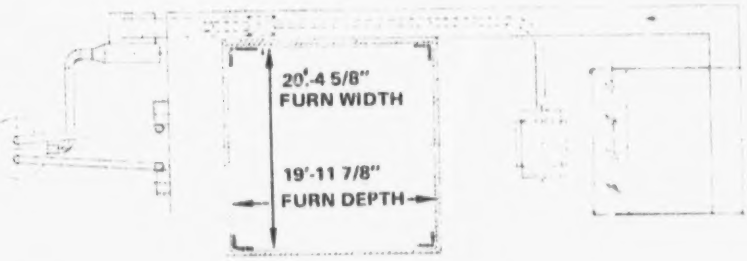
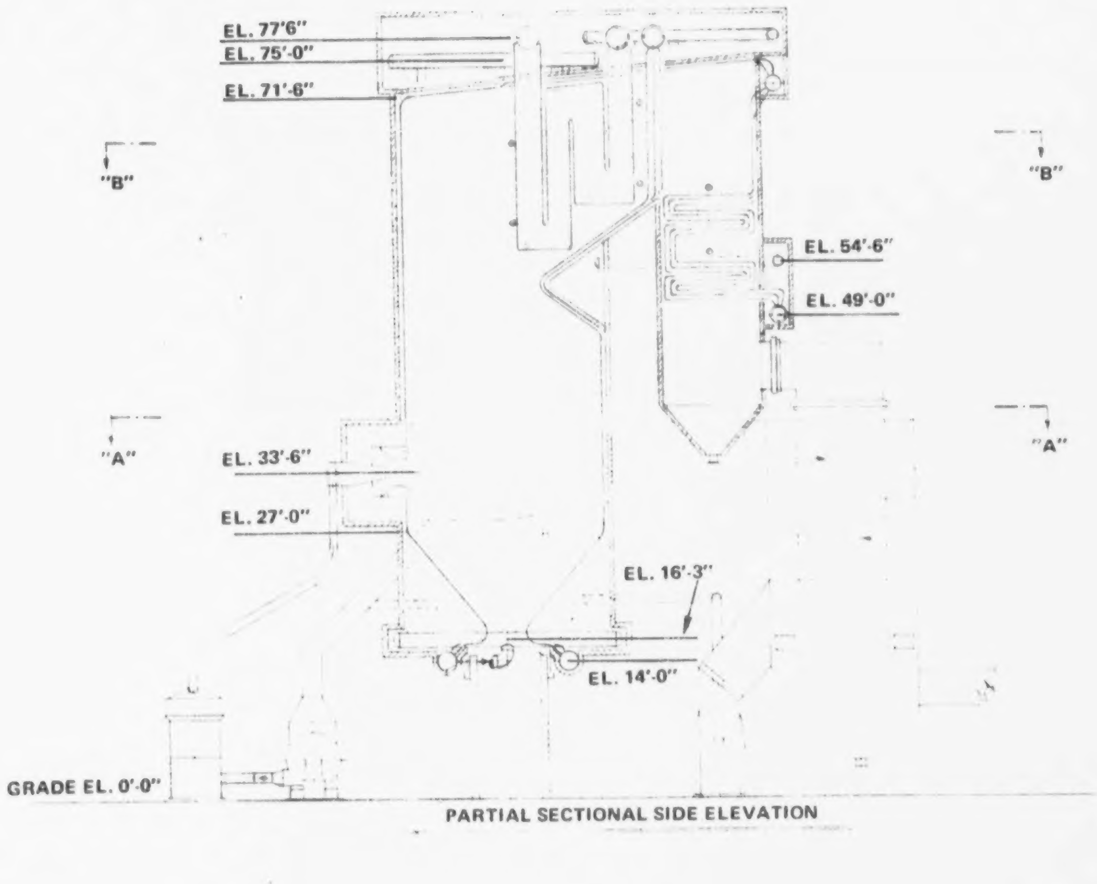
[*] Broadly speaking, Cases 5 through 10.



PLAN AT SECT. "B-B"


20'-4 5/8"
FURN WIDTH
19'-11 7/8"
FURN DEPTH

PLAN AT SECT. "A-A"


EL. 77'6"
EL. 75'-0"
EL. 71'-6"
"B"
"B"
EL. 54'-6"
EL. 49'-0"
"A"
"A"
EL. 33'-6"
EL. 27'-0"
EL. 16'-3"
EL. 14'-0"
GRADE EL. 0'-0"

PARTIAL SECTIONAL SIDE ELEVATION

FIGURE III-66. COAL-FIRED REHEATER FOR 100 MW ARCH FURNACE PLANT

TABLE III-25

REVISED COSTS FOR THE ARCH FURNACE PLANT

CAPITAL COSTS

FPC Codes	Description	Cost, 10^6 $
310	Land and Land Rights	0.47
311	Structures and Improvements	1.64
312	Boiler Plant Equipment	16.66
314	Turbine-Generator Equipment	5.39
315	Accessory Electrical Equipment	0.99
316	Misc. Power Plant Equipment	0.26
	Air Pollution Control Equipment	1.19
	Waste Handling Equipment	5.89
	Engineering and Inspection	2.08
	Total Capital Cost	34.57

ANNUAL COSTS

Annual Capital Cost, 10^6 $	5.26	(Effective Annualization rate, 15.2 percent)
Water Cost, 10^6 $	0.00	
Operating Labor, 10^6 $	0.49	
Maintenance, 10^6 $	1.05	
Coal Cost, 10^6 $	1.05	
Residue Disposal, 10^6 $	0.21	
Total Annual Costs, 10^6 $	8.06	
Annual Credit for Power Generated, 10^6 $	5.66	
Quantity of Waste Burned, 10^3 ton/yr	5.23	
Disposal Cost, $/ton	4.59	
Transportation Cost (3.00 Mile Haul Radius), $/ton	1.58	
Total Net Disposal Cost, $/ton	6.17	

concluded that, unlike Cases 3 and 10, the capital costs for Case 7 would prove stable or, at most, would undergo only minor change because of accuracy differences between the preliminary and detailed cost analyses.

Although the merit of the Case 7 system has thus increased in prominence due to the iterative analysis, other trade-off factors should also be considered. One such factor is that, in Case 10, the refuse-fired furnace would be operated at temperatures (exit steam = 750°F) well below those required for final steam conditions. This would be done to minimize corrosion and fouling. Case 7, however, is a single-furnace system in which the refuse ash will find wall temperatures corresponding to final steam conditions. Thus the availability of the Case 7 design may not prove to be as high as for the Case 10 system. As pointed out earlier, the optimization study of a suspension-fired system was prompted basically by projected technical advantages. In view of this rationale, it is felt that the arch furnace could still be the preferred configuration to explore in future construction, particularly if the design approach outlined here does prove unnecessarily conservative.

3. Retrofit Plants

Unlike the new construction designs, those for the retrofit systems were not competitively analyzed within a cost model. Such treatment was considered to be impractical because of the constraints imposed by the existing structures for which retrofit is to be considered. The most cost effective retrofit design may not be compatible with the steam conditions or boiler configuration of the unit that happens to be the most available for conversion. In the interest of creating a multiplicity of choices, all five of the retrofit systems were brought to the same level of design detail as were the two new-construction designs that were selected after competitive analysis had been performed.

In developing costs for the retrofit boiler plant equipment, costs were included for the removal of tubing, insulation and support steel. To keep the costs representative of a type of unit rather than a specific unit, the cost of moving boiler house equipment was not included. The new-material costs include all material and equipment furnished by the steam generator manufacturer, shop work, engineering, overhead and profit for the items covered in that category. A fixed fee was also included for the erection of the equipment; this included tools and erection equipment, expendables, erection supervision, and profit for the erection. The labor estimate used for the retrofit boiler plant equipment cost item was based on straight time for field erection labor ($10.00/man-hour).

All of the other items in the retrofit cost breakdown were based on the derivations developed for the cost model. Additional capital costs were included for new land to accommodate waste handling equipment, new structures pertaining thereto and to the retrofit boiler, add-on accessory electrical equipment, and extra APC facilities. The last cost item was based on the increased volume of flue gas that would be experienced when the design level of refuse is fired in the modified system. This fractional treatment may appear to be an unrealistic approach, but is the only logical way of apportioning APC costs between the actual (fuel) sources of the pollutants generated.

The results of this costing are shown in Table III-26, which of course does not include any of the capital or annual costs associated with the existing plant. The two entries for Modification 5, A and B, represent the design (A) shown in Section III, B, 5, and (B) the same design without water-cooled grate bars installed on the hopper walls. The latter design option may be feasible if the burn-out characteristics of the refuse particles suspended in the furnace prove favorable.

It can be seen by comparing the costs shown in Table III-26 and those roughly extrapolated from the data presented in Figures III-43 and III-44 that the disposal costs (excluding transport) for retrofitted plants would be lower than those for new construction plants of corresponding size and configuration*.

While this situation tends to favor the adoption of the retrofit approach, another consideration should be taken into account. The plant factor used in calculating Table III-26 was 80%, the same value used for the new construction systems. This value was observed to permit a more direct comparison of the two types of systems, but it may not be entirely realistic. The availability of the retrofit system may well prove to be considerably lower than that of a newly constructed facility. This could result not only from the fact that the retrofit plant would tend to experience more down-time due to age but also because the mode of firing would be more conducive to furnace problems. Unlike new construction Cases 3 and 10, all of the retrofit designs (except Modification No. 2) would yield steam temperatures in excess of 750°F in furnaces in which refuse would be fired. Thus a lower plant factor should be anticipated due to increased corrosion and fouling problems.

As plant factor is reduced, the amount of refuse fired and of coal displaced are also lowered. This results in a significant increase (13 to 20% for each 10% (relative) drop in plant factor) in the total net disposal cost. This can be seen in the following table.

SENSITIVITY OF DISPOSAL COST TO PLANT AVAILABILITY

	Total Net Disposal Cost, $/ton					
Plant Factor, %	Mod. 1	Mod. 2	Mod. 3	Mod. 4	Mod. 5A	Mod. 5B
80	2.15	4.37	3.59	2.52	5.01	4.25
70	2.54	5.07	4.19	2.98	5.82	4.94
60	3.05	5.96	5.00	3.59	6.92	5.91

---

*i.e., Modifications No. 1 and 4 can be compared with Case 2, No. 2 with Case 1, No. 3 with Case 7, and No. 5 with Case 6.

TABLE III-26

COSTS FOR RETROFIT SYSTEMS

Description	Mod. 1	Mod. 2	Mod. 3	Mod. 4	Mod. 5A	Mod. 5B
		Additional Capital Costs, 10^3 \$				
New Land	19.0	20.0	17.0	13.5	15.5	15.5
New Structures	292.0	905.0	228.0	276.0	218.0	218.0
Retrofit Boiler Plant Equipment	1,465.0	4,529.0	1,144.0	1,380.0	1,091.0	14.0
Accessory Electrical Equipment	146.0	453.0	115.0	138.0	109.0	109.0
APC Equipment	60.0	52.0	60.0	43.0	60.0	60.0
Waste Handling Equipment	734.0	816.0	2,080.0	524.0	2,940.0	2,940.0
Engineering & Inspection	203.0	477.0	259.0	170.0	310.0	221.0
Total Additional Capital Costs	2,919.0	7,252.0	3,903.0	2,544.0	4,743.0	3,577.0
		Additional Annual Costs, 10^3 \$				
Annual Capital Costs	423.0	1,050.0	586.0	370.0	710.0	538.0
Operating Labor	95.0	95.0	119.0	85.0	119.0	119.0
Maintenance	95.0	95.0	229.0	85.0	339.0	339.0
Residue Disposal	129.0	145.0	112.0	92.0	120.0	120.0
Total Additional Annual Costs	742.0	1,385.0	1,046.0	632.0	1,288.0	1,116.0
Annual Credit for Coal, 10^3 \$	560.0	545.0	517.0	420.0	483.0	483.0
Refuse Fired, 10^3 tons/year	278.0	292.0	247.0	198.0	226.0	226.0
Disposal Cost, \$/ton	0.65	2.87	2.14	1.07	3.56	2.80
Transportation Cost, \$/ton	1.50	1.50	1.45	1.45	1.45	1.45
Total Net Disposal Cost, \$/ton	2.15	4.37	3.59	2.52	5.01	4.25

It will be important, in considering the retrofit approach, to review carefully the past availability of the unit selected for modification and to allow appropriate compensation for the effect that refuse firing will have on plant factor.

IV. RECOMMENDATIONS

A. IMMEDIATE TECHNOLOGICAL OPPORTUNITIES

The intent of the present program has been to identify, characterize, and rate the probable cost-effectivity of various steam generation processes based on the use of refuse-fuel. Problem areas have been noted that clearly demand further study; boiler configurations have been suggested that never have been evaluated with waste fuels; systems have been described that have already been proved, but that have not been operationally optimized. As discussed in Section IV, B below, there is considerable work of an R&D nature that remains to be done. This does not mean, however, that immediate technical opportunities do not exist nor that the pursuit now of such endeavors will preclude the later application of benefits derived from R&D operations.

What is important is that many of the systems described in this report have already been or are being reduced to practice, if not with refuse at least with other waste fuels. A viable candidate design, considered appropriate for immediate construction in areas beset with SO_2 burdens and high disposal costs, is the Case 3 system. It is felt to be superior in design to a similar system that has already proved quite successful in Munich, Germany. The immediate construction of other type, proven systems can also be recommended; the selection, however, must also entail the consideration of cost criteria, as discussed in Section III, C, 1 and Appendix C.

This leads to an area wherein considerable immediate technical activity should be focused. The question of whether, as well as what type, combined-fired steam generators should be incorporated within urban waste management structures must be answered on the basis of local conditions. In many LMA's these have not been systematically defined. Thus work should be started immediately in many cities to determine how the present trends in refuse-disposal costs, energy needs, demographic distributions, and air pollution burden will influence decision making concerning future waste management policies.

B. SUGGESTED RESEARCH AND DEVELOPMENT PLANS

1. Overview

The criteria used for selection of R&D plans to enhance refuse combustion technology and a summary of the principal program areas recommended for study have been presented in Section I, C, 3. What is suggested is that Federal funds should be expended in engineering development investigations all slanted towards demonstrating the practicality and economy of using refuse as a low sulfur fuel.

In the pages that follow, the elements making up the key programs are discussed and cost estimates presented for each. This is done in the form of two plans; one (A) where it is assumed that $5 million would be available over a 5-year period, and the other (B) where $25 million would be expended over the same period. In both plans it is recommended that a $2 million central research facility be constructed in order to eliminate expensive equipment redundancies and to standardize test methodology. Long-term budgetary commitments are not yet being made for environmental projects and hence a programmed flow of monies cannot be assured. The questions of the manner in which lesser funding could best be spent or how to best assure maximum results from an irregular flow of funds will be key ones facing the EPA Project Officer.

Clearly if construction funds for the central facility cannot be committed early in the 5-year period then this recommendation should be eliminated and whatever funds are appropriated used for R&D. Most programs developed below would result in a moderately thorough understanding of the specific area under study and numerous distinct sub-elements of information would be generated, including those pertaining to the pre-processing, storage, and conveyance of refuse. Under conditions of less than anticipated funding, it would be necessary to reduce the overall scope of the selected programs, but the portion undertaken would still make a distinct contribution to refuse combustion technology. Thus, while a $300,000 effort in corrosion investigations would solve most of the current problems here, a $75,000 program would still greatly assist users in minimizing damage. Similarly, many millions of dollars could beneficially be expended in developing a better understanding of mechanisms and equipment leading to improved combustion efficiency, yet if only $750,000 can be budgeted, this will still permit construction of far more advanced systems than now possible. What phases should be eliminated of course will strictly depend on the state of knowledge in the U.S. and Europe at the time the allocation of priorities must be made. In the event of the availability of only, say, $1.5 million over a 5-year period, the broader areas suggested below should be narrowed to one chief subject (suspension firing, for example) for maximum cost effectiveness.

PLAN A

Central Research Facility:

The recommended research facility should be on the order of 15,000-20,000 sq. ft. in area. It would consist of basic office space for up to 30 persons, several small laboratories, a machine shop, a library, data recording room, a small photographic laboratory, storage facilities, a test cell for component evaluation, and a 2000-2500 sq. ft. high bay room for housing a research furnace. The design study, architect, construction, basic furnishings, and outside improvements are estimated to cost $800,000-$850,000.

Housed within the building would be a grinder (15 tph), analytical instrumentation, data recording equipment, a model facility, pollution control equipment, and the research furnace. Estimated costs for the basic equipment are $900,000-$950,000.

The remainder of the funds ($200,000-$300,000) making up the estimated $2 million facility cost are reserved for metal and plastic stock, chemicals, fuel, office supplies, equipment maintenance, library materials, and utilities over the 5-year period. Each project would be expected to purchase speciality materials and supplies as required.

PROGRAM 1 - COMBUSTION OPTIMIZATION STUDIES: BASIC PROGRAM

Scope:

Following a preliminary experiment-design effort, test work will be performed to ascertain the optimum furnace conditions under which the highest practical heat release rates can be achieved when firing refuse in certain selected modalities. This study will be performed using the small steam generator incorporated within the Central R&D Facility. Test operations will be limited to the evaluation of operating parameters compatible with conventional boiler configurations. "Non-conventional" thermal conversion systems will be similarly evaluated under Programs 8 and 9. Program 1 of Plan B, discussed below, aims at the same basic objectives as the present program, except that the firing modalities to be studied are more comprehensive and the degree of test parameterization more detailed.

Program Elements:

1.1

An 8-month period will be devoted to identifying and analyzing the relative importance of the various parameters that influence refuse combustion rates. This will require extensive perusal of the pertinent domestic and foreign engineering literature, as well as consultation with leading authorities in the field. The analysis will focus on both grate- and suspension-fired arrangements, but necessarily isolate the two processes as individual topics. Following this engineering study, an experimental test plan will be developed. With this plan, the various parameters influencing combustion can then be studied individually and in combinations to determine optimum operating conditions and configurations. It is estimated that the accomplishment of this phase will require an investment of $60,000.

1.2

Implementation of that portion of the test plan dealing with grate-stoked furnace configurations will be undertaken. As operating conditions are varied, heat release rates and degree of refuse burnout will be the principal parameters monitored. Because the boiler will be fully instrumented, data on air pollutant levels will be acquired at appropriate points in the test operations.

Combustion air management will be the primary control process studied. This will involve testing to establish the influence on combustion efficiency of air distribution between underfire and overfire inlets, of overfire air flow patterns, and of the amount of excess air used. The role of combustion air temperature will be evaluated.

Tests will also be performed to establish the effects of bed depth and grate speed on combustion rates. In these tests an artificial refuse will be used to insure constant feed compositions.

Accomplishment of this work will require 12 months, assuming that the Central R&D Facility is in complete operational status at the beginning of that time. The cost of performing this task element is estimated to be $300,000.

1.3

This task element will be similar in purpose to element 1.2, except that the firing style to be studied will be of the suspension type. The same basic boiler configuration will be used, except that the air and fuel addition systems will be those appropriate for producing suspension burning. The modality of ground refuse injection will be similar to that practiced with pulverized coal.

The key parameters of interest will again include heat release rate and degree of burnout, to which will be added particle residence time (in suspension) as a function of shape and density, injection velocity and paths, and specific combustion conditions. The effect of air management will be evaluated, particularly in terms of distribution between primary, secondary, and tertiary inlet points. Combustion efficiency will be established in terms of both excess air use and the gas vertical velocity and turbulence in the combustion zone. The test data obtained will also be related to air pollutant levels as well as particle size distribution and moisture content of the feed.

This task element can be completed in 12 months time and will cost $480,000 to accomplish.

1.4

A final task element of Program 1 will be the generation of guidelines which will help optimize the design and operation of combined fired installations. Development of this documentation will involve the systematic analysis of the data generated in the other task elements and extrapolation of the findings to scaled-up applications. Recommendations will be developed on the basis of selected, popular boiler configurations. This element will require 8 months to perform and will cost about $60,000.

PROGRAM 2 - CORROSION AND FOULING

Scope:

Investigations made during the last five years, including several on-going studies, have done much to elucidate the nature of corrosion and fouling when refuse is fired by itself or in conjunction with a fossil fuel. That these mechanisms need not be as harmful to continuous incinerator operation as was once believed is apparent from the history of numerous facilities and from the fact that new plants are being designed and built. Whatever the outcome of present research, however, it is clear that certain fundamental information concerning tube wastage must still be obtained if improved incinerator designs are to be made in the future. Mechanical "fixes" are now oftentimes employed and chemical elements contributing to attack are hypothesized rather than being scientifically verified. Prediction of the effect of a change in refuse composition or mode of firing cannot now be made with any certainty. As corrosion research has continued for the last 40 years within the chemical process industries, with the aim of developing ever superior materials or inhibiting processes, so must it continue in the steam generating industry, particularly when as heterogeneous a fuel as refuse is employed.

Program Elements

2.1

A continuing program (5 years) should be maintained at a level of $50,000 per year to investigate experimentally mechanisms of fireside tube corrosion and fouling. An approximate 50-50 division of effort between experiments in the laboratory under controlled conditions and in actual large boilers is recommended. Attention will be directed to the role that metals present in refuse play, in addition to sulfur, halides, alkali metals, and the alkaline earth metals. The role of reducing and oxidizing atmospheres will be studied in both steady state and cyclic conditions.

2.2

In addition to the above applied effort, it is recommended that a single $50,000 program of one year's duration be funded approximately half-way into the 5-year period, whose purpose would be to summarize the then best theories of the corrosion and fouling processes. Time phasing should be such that any suggested final experimentation could be accomplished under Program 2.1.

PROGRAM 3 - SYSTEMS ANALYSIS OF ALTERNATIVE THERMAL CONVERSION PROCESSES FOR REFUSE

Scope:

A number of independent studies have been made, both privately and with Government funding, to indicate the technical and economic feasibility of candidate processes for converting refuse into either useful or harmless chemical species. Temperatures have ranged from the few hundreds of degrees for reaction schemes with carbon monoxide*, through the intermediate temperatures of pyrolysis and conventional incineration, to the several thousand degrees of special high temperature furnace processes. Some schemes attempt to yield the minimum possible residue, while others deliberately strive to produce the maximum possible homogeneous gaseous, liquid, or solid fuel from the mixed refuse. While a simple ranking of the worth of the various alternatives can perhaps never be developed, in that plant size and local economics affect total costs to a significant degree, consistent data do not yet exist for indicating relative advantages under various conditions. A single program effort for generating such information should be undertaken.

Program Elements:

3.1

An 18-month program, to cost an estimated $200,000, will establish realistic cost information for making valid comparisons of alternative refuse conversion processes. Plant size, design features (including required pollution control equipment), energy requirements, and distribution or transportation costs will be examined in this analysis. Processes to be examined will include the principal ones currently considered to be within the state-of-the-art where self-generated or external heat is applied to refuse, with or without added chemical reactants.

PROGRAM 4 - PARTICULATE CONTROL

Scope:

It is not considered essential under the present plan to conduct any extensive amount of research into improvements of air pollution control equipment for refuse combustion in that the control R&D being supported or planned by EPA will be directly useful when refuse is employed as a fuel. Only programs where unique refuse effects are examined are considered here.

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*Composting temperatures might be considered to be the lowest of the various thermal conversion processes, but in that this is essentially a natural process, it need not be considered here.

Program Elements:

4.1

Only limited resistivity-temperature measurements have been made on fly ash resulting from combustion of refuse separately or in combination with coal. No measurements have been made under conditions of suspension firing. During a 12-month investigation whose estimated cost is $75,000, samples would be obtained and the necessary measurements made so that electrostatic precipitator operating conditions can be better defined. Chemical analysis of the ashes will be made in order to identify any correlations with fuel composition and to permit examination of the concept of additive injection for altering resistivity.

4.2

The EPA office concerned with solid wastes is sponsoring work on novel incineration techniques where removal of particles at high temperature is important. It is recommended that this work be assisted by the addition of $125,000 of air pollution control funds to on-going programs.

4.3

The influence of under- and over-fire air on particle carryover is still not fully understood. Within the central research facility furnace, studies will be conducted that will permit the design of air introduction systems with minimum formation, pick-up, and transfer of ash. Both high speed photography and probe samples will be utilized, with fly ash loading, size distribution, and loss on ignition being measured. Limited tests will also be conducted in the suspension firing mode. Equations will be derived describing the phenomena observed. This program element will require 18 months for completion and the estimated cost is $300,000.

PROGRAM 5 - SMALL REFUSE-FIRED BOILERS

Scope:

Present studies on the use of refuse as a low sulfur fuel have concentrated on facilities where many hundreds of tons per day of refuse could be made available. Because of the magnitude of the urban solid waste problem and the economics of scale for large operating plants, attention was logically directed initially at these waste levels. Refuse collection and haul costs in high population density areas has become so expensive, however, that economical operation of smaller district boilers might prove possible. The extensive rebuilding of many downtown areas now permits consideration of incorporation of such new facilities in conjunction with apartment and commercial heating networks.

Program Elements:

5.1

In a $100,000 12-month study, an analysis will be made of the incremental cost of present refuse disposal practices vs air pollution-free district refuse boilers. Both addition of the necessary equipment to current construction and to redevelopment areas will be examined. Cost equations will be generated indicating relative advantages over a range of large city practical conditions.

PROGRAM 6 - SUB-SCALE COMPONENT TESTING

Scope:

Incorporation of new innovations into refuse combustion systems has been hampered by a lack of economic incentive plus the inability of most developers of a new concept to test their device under realistic conditions. The availability of the central research facility will do much to accelerate current new product cycle times. Equipment that could be considered for evaluation at that facility includes grate systems, combustion air introduction schemes, transport devices, analytical and control instrumentation, pollution control apparatus, size and component classification units, and heat transfer systems. Most of this equipment would of course be smaller in size than that to be employed in full-scale plants.

Program Elements:

6.1

It is to be hoped that a significant number of the items of equipment to be evaluated would be loaned, or furnished at minimum costs, by interested vendors and developers. An allocation of $200,000 per year for three years should permit the assembly of the various devices into the research furnace and the conducting of sufficient tests to ascertain the inherent value of the concept. An exact listing of the items of course cannot be made at this time.

PROGRAM 7 - FLOW MODELING

Scope:

Limited European experience has demonstrated that studies of incinerator flow characteristics in scaled models can yield valuable information for improvements in large heat recovery systems. Effects on mixing conditions (within the fuel bed and external to it) and on fluid dynamics relative to heat transfer surfaces can be ascertained in relatively inexpensive equipment, thus leading to superior combustion efficiency and reduced corrosion. This area of investigation should encompass theoretical considerations of flow dynamics, design and fabrication of a versatile model, and the conducting of a series of experiments within the model.

Program Elements

7.1

A 12-month survey of European and U.S. experience in incinerator modeling will be made; a budgetary requirement of $70,000 is estimated. From a review of literature, interviews with authorities in the field (both in general fluid modeling and specific incinerator modeling), and an analysis of the current needs for improved design features, a report will be issued describing potential benefits to be realized from an experimental modeling program. An outline of the recommended R&D tasks will be included in the report.

7.2

The second phase effort within this program will consist of a 6-month detailed design of modeling equipment. $60,000 will be required to complete this task to the point of working construction drawings and purchasing specifications. Elements 7.1 and 7.2 can be accomplished while the central R&D facility is under construction.

7.3

Construction of the experimental modeling device will cost $55,000, of which approximately $25,000 will be for material and components. Nine months will be required to complete this element through check-out of the system.

7.4

The last program element, requiring $115,000 and 18 months to complete, will consist of an experimental study of the effect of variations of design features on flow dynamics. Only features specific to refuse-fired (and combined-fired) systems will be studied. Flow conditions around an economizer section, for example, would be given attention only in those cases where design improvements in a refuse-fired economizer are sought. Because of possible unique corrosion from refuse constituents, work will not be limited to the initial heat transfer zones only, but will be conducted through upper pass sections where stagnation or local reduction may lead to tube wastage.

PLAN B

PROGRAM 1 - COMBUSTION OPTIMIZATION STUDIES: EXPANDED PROGRAM

Scope:

The rationale of this program is essentially the same as that of Program 1 of Plan A. The scope, however, is broader in that the firing modalities to be studied are more comprehensive and the degree of test parameterization more detailed. In terms of comparative benefits, the present program will furnish guidelines for combustion optimization for a much wider range of refuse-fired boiler designs. The purview, however, is still limited to conventional boiler configurations and stoking processes.

Program Elements:

1.5

As task element 1.1, the present one will consist of a technical review and analysis effort and culminate in the development of a test plan. The technical review effort will be identical to that of element 1.1 of Plan A. The test plan development will, however, be considerably expanded so as to include the additional experimental work described below in the test-oriented task elements of the Program. The present element can be carried out in an 8-month period at an estimated cost of $80,000.

1.6

All of the work described for element 1.2 will also be performed in the present element. When optimum firing conditions have been established for the agitating-grate furnace incorporated in the central R&D facility, the following additional work will be performed. The removable grate assembly will be replaced with two other styles, and the tests accomplished in element 1.2 of Plan A repeated to determine if the same or different optimum conditions prevail. The sub-scale grates tested should provide evaluations of the roller, forward-reciprocating, and one other type selected at the discretion of the contractor. The grate configuration providing the best combustion effects will then be used in the subsequent tests of this element.

Further test work will be addressed to the evaluation of refuse composition on combustion characteristics. In order to minimize compositional changes due to dehydration, the feed material will be artificially prepared by blending, prior to firing, various proportions of the usual ingredients. The ultimate analyses of these constituent will be obtained prior to blending. The purpose of these tests will be to verify combustion calculations and to determine the point at which auxiliary fossil-fuel firing would be warranted for fuel degraded by prior salvage operations, weather, or compositional fluctuations of a seasonal or local nature.

A final experiment in this task element will be aimed at evaluating the benefits of pulsed underfire oxygen on combustion efficiency. The process of periodically introducing pure oxygen into the bed will doubtless increase burning rates and the degree of burnout. In the context of the present program, utilization of oxygen will be explored from the point of view of combustion control and the promotion of more even output steam conditions. If such control proves feasible, process costs will be compared with the alternate approach of using auxiliary fossil fuel.

The task element just described will require a technical effort lasting 18 months and a funding input of about $450, 000.

1. 7

This element will involve all of the experimental work described for element 1. 3 of Plan A, plus certain additional tasks. In accomplishing the element 1. 7 work, however, a more refined testing configuration will be employed. The agitating grate will be removed from the boiler and a hopper bottom installed to better reproduce the effects operating in full-scale structures. Similarly, the fuel injection nozzles to be evaluated will be of both the horizontal and tangential types. This will permit comparisons to be made of these two popular types of gun orientations.

When the objectives detailed for element 1. 3, as expanded in the previous paragraph, are accomplished, the role of refuse composition on suspension-firing efficiency will be evaluated. This work will essentially conform with the operations described in the second paragraph of element 1. 6.

In this test work, the pneumatic feed-flow process will be designed on the basis of recognized test apparatus interface requirements. For practical extrapolation of the optimization study results, it will be appropriate that the configuration of full-scale conveyance systems be understood and identified. Thus, studies will be conducted, wherein commercially available components will be catalogued, appraised, and usable combinations proposed as candidate designs. This survey will not be limited to hardware appropriate only for the type of steam generator considered on this task element, but to other (e. g., the arch furnace) suspension-fired configurations as well.

This element of the program should be completed in 14 months. Project costs will come to about $550, 000.

1.8

On this program element, optimization of the spreader-stoker firing modality will be attempted. This will involve modification of the Central R&D Facility test boiler. The installed agitating grate will be replaced with a sub-scale traveling grate and the charging chute removed to accommodate the other type stoker. The experiments performed on this modification of the test boiler will essentially parallel those described in element 1.7 involving suspension firing. That is, the effect on combustion efficiency exerted by such parameters as combustion air quantities and distribution, particularly secondary or propulsion air, injection velocity and paths, and feed consist will be determined. This task element will also involve consideration of the commercial hardware, pneumatic and mechanical, for providing the desired stoking effect when operating with ground refuse of various top sizes. Equipment suitable for providing the sought-for function will be identified and described.

Existing spreader-stokers, firing waste fuels, generally employ travelling grates to catch the burning furnace fall-out. Because this practice may actually be more traditional than inventive, consideration will be given to possible alternative forms which might furnish superior burn-out characteristics. An example would be the use of a catch-hopper in which partially burnt-out refuse particles would be suspended with underfire air until elutriated from or precipitated to the bottom of the fluidic system.

Execution of this task element will involve an expenditure of about $520,000 and between 14 and 16 months of time to accomplish.

1.9

A viable furnace-form for suspension firing is the arch furnace. It is not anticipated, however, that this particular configuration can be easily reproduced in the multipurpose test-boiler which will be installed at the Central R&D Facility. The cost of designing and erecting a sub-scale boiler of this type would probably exceed that implicit in converting or rehabilitating an existing power boiler. It is expected that any needed negotiations, such as for boiler use or refuse delivery, would be consummated prior to the initiation of the present task element.

Modification operations will include the installation of a pneumatic refuse injection system; selection of this hardware will be based on the guidelines established on element 1.7. Because anthracite coal will not be acceptable as an auxiliary fossil fuel, auxiliary burners, firing oil or natural gas, would also be installed. Appropriate ancillary equipment will be erected to permit the receipt, movement, size-reduction, and feed conveyance of the refuse. As necessary, plant instrumentation will be upgraded or augmented so that all test parameters of interest can be properly monitored.

Test operations, although of full scale, still will essentially conform with the work outlined for element 1.3. It will not of course be practical to use artificial refuse. For this reason, the stored, shredded fuel will require frequent, composite sampling and analysis.

Assuming cost-free access to the boiler and delivery of refuse, it is estimated that this work element will cost $1,250,000 to perform and a minimum of 2-1/2 years to carry out.

1.10

The purpose and approach of the present task element is the same as that of element 1.4 of Plan A. The level of effort will be somewhat greater, however, because the documentation of design and operational guidelines for optimized combined-firing will, in the present element, embrace a wider technical scope. The cost is therefore estimated to be $100,000 to be committed over a period of 8 months.

PROGRAM 8 - EVALUATION OF REFUSE PYROLYSIS AND GASIFICATION PROCESSES IN CONNECTION WITH STEAM GENERATION

Scope:

Considerable interest focuses on non-combustive processes wherein various materials are pyrolyzed to yield solid, liquid, and gaseous products having significant fuel values. In the case of refuse, full-scale systems that incorporate this process are now being built. The refuse treated in such equipment will undergo considerable volume reduction and the emitted gases can be burned without the production of fly ash. It has also been demonstrated that the pyrolyzate gases can be fired to drive a gas-turbine and thus produce power. The same feed gas and, perhaps, the carbonaceous bottom residues from the pyrolyzer can probably be fired in a conventional boiler to generate steam. The question is would it be economically practical to do so, assuming that optimum process conditions had been established.

The purpose of the present program will be to determine, through appropriate analysis and pilot test work, optimum design and operating conditions for a pyrolysis-type fuel generator. Process costs would then be systematically analyzed to establish the merit of the approach.

Program Elements:

8.1

As an initial step, an updated state-of-the-art survey will be conducted. A preliminary engineering analysis will then be performed to establish the preferred design configurations and operating conditions. At this time, problem areas requiring subsequent treatment will be defined.

A preliminary study will then be made to determine if the process is economically feasible in terms of steam generation applications.

This work can be done in 6 months or less at a cost of about $50,000.

8.2

Bench scale work will be undertaken on this task element to verify or furnish needed information concerning the pyrolysis process. The areas of test activity requiring particular emphasis will have been defined on task element 8.1. Generally, however, this work will serve to insure that subsequent equipment design is properly based. Latent heats of pyrolysis for different refuse constituents, and mixtures thereof, will be measured. The heating value of process vapors and char produced at different pot temperatures will be determined. The effect of different levels of contaminant oxygen in the heating gas will be parameterized. The function of refuse grind-size on heat transfer and, thus, on pyrolysis rates, will be established. Corrosion phenomena will also be studied, so that proper materials of construction can later be selected. The composition of condensibles removed at different temperatures from the pyrolyzate vapors will be undertaken. This will help determine whether any particular fraction is worth isolating for further processing to chemical markets. Similarly, pot residues will be analyzed to determine possible values other than for heating.

The amount of laboratory effort which will actually be required on this task element cannot be accurately estimated at this time. It is likely, however, that the expenditure will not exceed $250,000 nor require more than 2 years of committed time.

8.3

The design of a pilot plant will be undertaken on this program element. Engineering drawings and specifications suitable for subsequent construction work will be generated for the pyrolyzer itself and all necessary ancillary installations. Cost estimates for the complete plant will then be derived.

The plant will be fully instrumented so that heat distributions and material flows can be recorded. Among the control systems provided will be one for transferring excess energy from the char-fed fire box so that the desired level of pyrolysis will be sustained. This heat will be transferred to the product fuel-vapor or, possibly, to a steam loop.

Coupling the unit to a steam generator would be costly and serve no great purpose. Therefore, a simple combustion chamber will be provided to permit burnoff of the products and possible recycle at reduced temperatures.

This effort will require 9 months to complete and cost about $300,000.

8.4

The construction of the pilot plant will be accomplished on this task element. A plant throughput of 10 tph is anticipated. Using rough rule of thumb estimates, it can be expected that the complete turnkey system will cost about $1,800,000. A minimum of two years should be allowed for work completion.

8.5

Pilot plant studies will be conducted for a period of 18 months. The principal purpose of this work will be to determine the operating conditions under which maximum energy can be produced and delivered to the use point without deleterious effects to the system or to the atmosphere. The effects of fuel variations and the presence of different levels of oxygen in the pyrolyzer will also be studied. Deleterious combustion products resulting from the firing of both the fuel vapor and the char will be identified and quantified. Design improvements will be made in the course of the work wherever feasible.

This task element will require a funding of about $600,000.

PROGRAM 9 - EVALUATION OF REFUSE COMBUSTION IN FLUIDIZED BEDS

Scope:

The fluidized bed is now being investigated as a potential furnace configuration for coal-fired boilers. Because of the fuel suspension afforded by the combustion air, uniform temperature distributions are achieved and close positioning of heat exchange surfaces is possible. This results in greatly increased heat exchange rates so that the heat exchange surface can be correspondingly reduced. The net effect is that the boiler can assume considerably smaller size and cost. A further benefit is that solid air pollutant absorbents can be suspended in the bed with the fuel to reduce emissions (e.g., lime can be added to remove SO_2).

This same configuration may also prove technically feasible* and cost-effective for firing ground refuse. The range of particle sizes of shredded refuse is much greater than that of the corn coal typically fired in such test boilers. This problem can be managed, however, by certain design features the success of which has already been demonstrated in various hybrid systems.

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*Current work being done in this area suggests this to be the case.

The purpose of the present program will be to investigate the feasibility of the process, assess the technical problems associated with it for refuse disposal, and develop designs for, build, and test an optimum configuration thereof.

Program Elements:

9.1

A state-of-the-art survey will be made as the initial step in this element of the program. The assembled information will then be systematically analyzed and related to theory. From this basis and the well-developed technology associated with fluidized systems, a feasibility analysis will then be conducted. In support of this effort, laboratory and field work will be performed to furnish the analysts with needed data on the shape factors, particle size distributions and densities, and compositions of refuse fractions obtained from typical size-reduction machinery. It is anticipated that this analysis, grounded on well-established fluid mechanics, will demonstrate that the fluidized bed in itself will not be a suitable furnace configuration. Appropriate modifications will doubtless have to be designed to provide proper fuel behavior. The design recommendations that are generated will be a critical output of this program element.

The study described will require a technical effort lasting about 5 months and requiring an outlay of approximately $40,000.

9.2

Bench work will be pursued on the present task element to validate the conclusions developed on program element 9.1. Small scale apparatuses will be constructed and operated to study the process designs previously produced. Because the characteristics of fluidized systems respond with considerable fidelity to scale-up, initial design optimization will be attempted while at the bench. Matters to be evaluated will be: (1) the use of an inert, solid phase for heat transfer; (2) gas velocities; (3) feed-reduction requirements; (4) bed geometries; (5) excess-air effect; (6) feed rate vs bed volume; (7) heat transfer rates; and (8) effectiveness of hybrid features for managing quickly elutriated materials and dense precipitates.

Assuming that process feasibility is proved, this work will culminate in the generation of specific design recommendations which will be utilized in the next stage of work. The cost of accomplishing this element of the program will be about $750,000 and should be done in approximately 2 years time.

9.3

On this program task, preliminary full-scale boiler designs will be developed initially and cost analyzed in comparison with other possibilities. The results will be documented to provide a decision-basis for proceeding with pilot-plant-level testing. This process cost-evaluation should be completed in about 4 months at a cost of about $35,000.

9.4

Pilot plant design will be undertaken on this program element. Drawings, specifications, and costs for a unit capable of firing 100 tpd of refuse will be generated. Because it will be economically impractical to assess the quality of the output steam using a turbine-generator set, standard enthalpy measurements will be used instead, and the product condensed for subsequent reinjection as feed water. The ancillary equipment requirements will closely approach those of the pilot-plant utilizing the pyrolysis principle.

This design effort will require support to the amount of about $300,000 and entail a time commitment of 1 year or more.

9.5

Construction of the fluidized-bed pilot plant for firing refuse can only be approximately estimated at this time. It is obvious, however, that high quality steam circuitry must be provided within the boiler itself and even into the preliminary loops of the condenser, thus imposing expensive hardware requirements. As a rough order of magnitude, complete plant costs will probably exceed $1,100,000. The time for plant construction will likely require at least 2 years of work.

9.6

Operation of the pilot plant will essentially involve the validation and/or amendment of the conclusions developed on element 9.2 of this program. Sustained firing of the pilot plant will also allow the acquisition of needed data on air pollutant emissions, corrosive effects, control and instrumentation requirements, and the handling of input and output solids. Design improvements will be effected as the need is recognized and insofar as correction is feasible.

Because of previous bench work, pilot test work need only be conducted for a period of 1 year. The cost will amount to about $775,000.

PROGRAM 10 - ENGINEERING MANUAL FOR THE CONVERSION OF BOILERS TO COMBINED FIRING

Scope:

The conversion of existing boilers to refuse firing is an attractive approach for gaining the sought-for capability. The initial investment costs are much lower and construction time much shorter than for building a new plant. A problematic aspect in the planning of conversion operations is that the technology is novel. This will handicap the executives of utility companies in their decision making and costly design errors could be made by the engineering firms retained. What will be needed is a reservoir of information from which engineering and economic guidelines can be extracted to deal with the major aspects of any given conversion operation.

The manual developed on the present program will provide specific information on how to select a boiler from the bases of condition, type, and the urban interface. Instructions, including structural drawings and specifications, will be provided with which to implement boiler retrofits. All major classes of fossil-fuel-fired boilers, which are suited to conversion, should be covered. The lay-out of the various types of refuse handling facilities will be explained and architectural details provided. Information will also be provided on the performance characteristics of refuse handling devices, including those incorporated into the steam generator itself. Costs for effecting the various types of conversions possible will be detailed, as will be the operating and maintenance costs associated with refuse firing.

Although it is obvious that this program should not be conducted by a firm in the utility-boiler manufacturing business, it will be important that the cooperation of all boiler manufacturers operating in this country be gained. It will therefore be highly desirable that the American Boiler Manufacturers Association (ABMA) not only endorses this undertaking but lends its support to it. The task elements outlined below have been developed on the basis of that assumption.

Program Elements:

10.1

The first step necessary will be to establish a catalog of boiler types suited for conversion. Obtaining this information will require a canvass being made of both boiler users and manufacturers. Implicit in this undertaking will be the prior development and dissemination of explanatory material, listing the criteria for retrofit suitability. A canvass will also be made of the manufacturers of refuse handling equipment for design information, performance specifications, and costs of their equipment.

An analysis will be made of the boiler data obtained and the dominant design forms classified into generic groups. Working arrangements with the ABMA and its member firms will be organized.

This preliminary effort will cost only about $15,000 but a minimum of 9 months must be allowed for its accomplishment. That rapid reaction to canvass inquiries should not be expected is fully understandable, considering the proprietary nature of the information solicited.

10.2

This task element will comprise the bulk of the design input required for the preparation of the manual. One or more candidates will be selected from each of the generic boiler groups and identified with the various retrofit options that can be considered practical. Design modification requirements will then be incorporated into a suitable plan-format for each of the candidates. These will then be submitted to the manufacturer of the boiler chosen, who will review, improve as necessary, and prepare the retrofit-design information, drawings, and cost data required. This will require of course that a subcontract arrangement be negotiated. Hopefully, all of the major manufacturers of utility-class boilers will share in this undertaking.

It has been roughly estimated that this task will involve an expenditure of $75,000. A minimum of 18 months should be allowed for its completion.

10.3

This task element will be devoted to the actual preparation of the engineering manuals. Initiation of this work need not wait upon the completion of elements 10.1 and 10.2. Document development will require 1 year's time and an outlay of about $235,000.

PROGRAM 11 - DESIGN OF DEMONSTRATION UNIT

Scope:

The culmination of the 5-year plan will be the design and construction of a full scale plant. Operation of such a station will demonstrate the degree of accuracy achieved in the previous design optimization while, at the same time, revealing opportunities for improvement in future units.

On the present program, all required design work will be accomplished. This will start with the interrelated matters of design and site selection. Civil engineering and geological surveys will then be conducted. Preliminary plant layouts and architectural sketches will then be developed and reviewed with the operators for go-ahead. Detailed facility designs will then be generated together with all necessary drawings, specifications and bid documentation. A construction schedule, based on the critical path method (CPM), will be developed and preliminary cost estimates for the complete turn-key system prepared.

All of the material and information will be incorporated or appropriately referenced in an overall planning document. This instrument will outline the basic strategy to be followed in clearing the legal pathway to ground-breaking, pursuing construction, and placing the finished system in successful operation.

The program work described herein is based on the assumption that an operator (possibly a grantee) has previously been designated. It is also assumed that a plant throughput of 1000 tpd is compatible with the requirements of the operator.

Program Elements:

11.1

In this initial task the type* of plant best serving the operator's interests will be established. Sites available to him will then be systematically analyzed and the optimum one designated. Based on this choice or the best possible compromise, the operator will commit himself to preliminary design specifications and sketches of the system considered optimum for the operator will be developed. These will be submitted for review and approval by the operator and the Government.

The site will then be submitted to a complete survey so that soil conditions, easements and encumbrances (particularly with respect to water access), underground and above-ground services, rights-of-way (to the grid or steam system, whichever applies), and adjoining traffic patterns are duly recorded.

Plant layouts** with corresponding architectural sketches will then be prepared and a selection made based on operator and Government concurrence.

This preliminary design work will require a minimum of 6 months to accomplish and require funding in the amount of $100,000.

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*Turboelectric, district or process steam, etc.

**Including all input/output service connections.

11.2

Detailed designs and specifications suitable to fully guide construction operations will be generated for all plant components save those standard items which are available off the shelf and conform with specifications. Boiler design will be accomplished by an ABMA member by special sub-contract.

Because the plant will be a demonstration unit, it will be important that a high degree of instrumentation be designed into it. This will include not only the requisite feed-back control systems, but read-out equipment capable of furnishing multi-point information on a number of parameters not normally monitored in conventional steam generators.

Suitable legal instruments will be prepared to permit the competitive procurement of the required work and material. This element of the program will cost about $700,000 to perform and will require a minimum of 18 months to finish.

11.3

A summary construction-plan document will be the principal end-item of this element. It will furnish a complete description of the plant, and outline all of the procedural steps which must be taken to arrive at a successfully operating plant. Developed for inclusion in it will be a breakdown of estimated costs, a CPM construction schedule, and an operation and maintenance plan, complete with manning recommendations.

Development of this documentation can be initiated before the completion of element 11.2. Costs will be about $200,000 for an 8-month period.

PROGRAM 12 - CONSTRUCTION OF DEMONSTRATION PLANT

Scope:

All necessary fabrication and erection work will be performed to complete turn-key system designed on Program 11.

Program Elements:

The construction program will be carried out in the standard CPM manner under the prime contractorship of a competent Architectural and Engineering firm. Completion of the work will require about 3-1/2 years. Actual plant costs are difficult to estimate at this time, but if Government participation is foreseen, about $10,000,000 should be planned for its share of the costs.

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